Journal of Architectural Research and Development

BIO-BYWORD SCIENTIFIC PUBLISHING PTY LTD
(619 649 400)
Level 10
50 Clarence Street
SYDNEY NSW 2000

ISSN (ONLINE): 2208-3537
ISSN (PRINT): 2208-3529

Journal of Architectural Research and Development

Focus and Scope

Journal of Architectural Research and Development is an international peer-reviewed and open access journal which is devoted to establishing a bridge between theory and practice in the fields of architectural and design research, urban planning and built environment research.

Topics covered but not limited to:

- Architectural design
- Architectural technology, including new technologies and energy saving technologies
- Architectural practice
- Urban planning
- Impacts of architecture on environment

About Publisher

Bio-Byword Scientific Publishing is a fast-growing, peer-reviewed and open access journal publisher, which is located in Sydney, Australia. As a dependable and credible corporation, it promotes and serves a broad range of subject areas for the benefit of humanity. By informing and educating a global community of scholars, practitioners, researchers and students, it endeavors to be the world's leading independent academic and professional publisher. To realize it, it keeps creative and innovative to meet the range of the authors' needs and publish the best of their work.

By cooperating with University of Sydney, University of New South Wales and other world-famous universities, Bio-Byword Scientific Publishing has established a huge publishing system based on hundreds of academic programs, and with a variety of journals in the subjects of medicine, construction, education and electronics.

Publisher Headquarter

BIO-BYWORD SCIENTIFIC PUBLISHING PTY LTD
Level 10
50 Clarence Street
Sydney NSW 2000
Website: www.bbwpublisher.com
Email: info@bbwpublisher.com

2025, Volume 9, Issue 5

Table of Contents

Journal of Architectural Research and Development, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Application of BIM in Developing Countries and Implications

Shuxing Kang, Jia Wu

School of Architecture and Civil Engineering, Jinggangshan University, Ji'an 343009, Jiangxi, China

Abstract: Building Information Modelling (BIM) technology can solve construction issues from multiple perspectives, including technical and managerial. While existing research has primarily focused on BIM's benefits and framework development, few studies discussed whether BIM can be successfully applied in developing countries. This paper examines the current status and key obstacles hindering BIM adoption in developing countries, analyzing their underlying causes. Notably, the study reveals that high BIM awareness does not directly lead to high BIM usage. The findings aim to provide theoretical support for enhancing the BIM environment and increasing implementation feasibility in developing countries. Additionally, the research identifies critical barriers for governments to address in promoting BIM adoption, offering a foundation for policy formulation.

Keywords: BIM; Obstacles; Developing countries

Online publication: September 26, 2025

1. Introduction

The use of BIM technology in the engineering field has been recognized by construction industry in recent years. The construction visualization, collision detection, and other functions are of great significance in reducing design changes and controlling costs. However, implementing BIM requires advanced construction technology, a high level of information technology, computer skills, and open construction culture. BIM may be difficult to implement in developing countries due to limitations such as the overall low level of information technology and the lack of BIM standards. Existing research focused on the benefits of implementing BIM in developing countries and developing new BIM frameworks, with few articles discussing the feasibility of implementing BIM in road construction in developing countries. However, it is necessary to study the feasibility of implementing BIM in developing countries. This is because research in this area can contribute to providing guidance and theoretical support to developing countries in formulating policies to promote BIM development. This paper aims to identify the main obstacles of BIM implementation in the road construction sector in developing countries and provide feasible solutions to improve the feasibility of BIM implementation for the road construction sector in developing countries.

2. Research methodology

This study uses a literature review as the main instrument to reach the research purpose by finding previous research on BIM topics in the road construction industry of developing countries. Some of the articles reviewed are about the implementation of BIM in the field of housing construction in developing countries. Although they do not belong to the field of road construction, the internal logic in terms of investment decisions, design optimization, cost reduction, and operation stage maintenance is similar to the field of road construction. By using a literature review, the author can quickly understand the current state of research on the implementation of BIM in the road construction sector in various developing countries and thus identify research gaps. The literature considered for this study was published between 2007 and 2022 and was mainly in English. Some government reports written in other languages were also referenced because they provided data to understand the local implementation of BIM. The methodology of the literature review for this paper is shown in **Figure 1**.

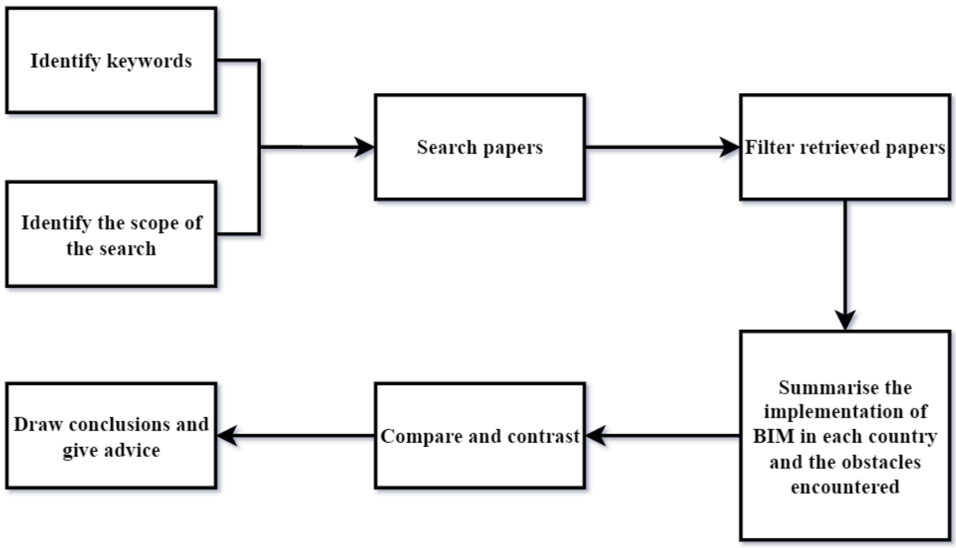


Figure 1. Methodology of literature review

To collect relevant papers for literature review, the following keywords and Boolean phrases were used:([Building information modelling OR BIM] AND [Developing countries] AND [road construction] AND [Obstacles OR Barriers] within [Title/ Abstract/ Keywords]) [1]. The repositories used in this paper include Scopus, ScienceDirect, Institution of Civil Engineers (ICE) virtual library, American Society of Civil Engineers (ASCE) library, and Google Scholar. Scopus is an abstract-only academic search engine, which was used for quick searches of relevant literature in this study. Science Direct provided both abstract and full text; it was used to view the full text of the paper, which was retrieved in Scopus.

3. Findings

In Malaysia, although the relevant government departments have made great efforts to promote BIM and enhance BIM education, the pace of implementation of BIM in Malaysia is still lagging [2, 3]. After the Malaysian government first used BIM for government projects in 2010, the construction industry development board was committed to helping the implementation of BIM to thrive in Malaysia. For example, adding BIM courses in university curricula and promoting the benefits of using BIM at construction industry conferences [4]. However, the result is not satisfactory. A survey finds that only 13% of Malaysian architectural firms used BIM in 2021 [5]. In this survey, the use of BIM technology was significantly higher in the public sector (8.2%) than in the private sector (4.9%). The reason for this may be that the public sectors desire to lead by example and to drive the implementation of BIM across the industry. The majority of companies in this survey do not use BIM due to a lack of BIM knowledge, insignificant economic benefits, and awareness issues, which have existed since 2013 in Malaysian construction industry. This shows that the policies implemented by the Malaysian government in recent years have not been effective in raising the level of BIM mastery among construction industry practitioners. Another study by Azmi *et al.* also shows that most people have a very limited grasp of BIM, saying they have only experienced it and are still learning [6]. Even though all investigators in this study agree that BIM will bring benefits to the projects, the construction industry is still reluctant to use the technology. Overall, although the Malaysian government has made some efforts to encourage and promote BIM in terms of publicity and education, and the public sector is taking the lead in using BIM, the BIM usage rate is still very low. The lack of a mandatory BIM policy may be one of the reasons for the low usage of BIM in Malaysia.

In India, most construction industry practitioners are willing to use BIM, but the use rate is low. An eight-month survey conducted by Klynveld Peat Marwick Goerdeler (KPMG) and Royal Institution of Chartered Surveyors (RICS) in major Indian cities revealed that approximately 78% of Indian respondents who were aware of BIM expected to start using it, but only 22% of industry players were currently using it [7]. In India, BIM is not implemented throughout the project lifecycle. BIM is mainly used in the pre-project phase and rarely in the operation phase [8–10]. The survey by KPMG and RICS shows that, in Indian projects, BIM was mainly used in the design and development phase (79.9%), followed by the construction phase (59.5%), with only 12.2% continuing to use BIM in the operation phase. The fact that the three most used functions of BIM among the Indian respondents were design coordination, clash detection, and quantity measurement also indicates that the use of BIM in India is still largely focused on the pre-project phases, such as design and tender, but not the whole project lifecycle. Other reasons for the low usage of BIM in India include the lack of BIM talents, lack of mandatory policies, and unclear economics return [8, 9]. There is a lack of structural, mechanical, electrical, and plumbing consultants skilled in the use of BIM in India [7]. So, although clients expect to use BIM, projects may still be unable to use it due to a lack of skilled staff. Moreover, although the construction industry associations in India are encouraging the implementing BIM, the government has not yet introduced mandatory provisions for companies to use it. The lack of regulatory guidance and mandatory provisions from local governments has also slowed down the development of BIM within India.

In China, BIM is widely used but concentrated in public projects [11]. Around 51.27% of companies in the construction industry are using BIM in more than half of their projects [12]. In government projects in tier 1 cities like Beijing and Shanghai, the BIM usage rate reaches 85.15% [13]. The implementation of BIM in China has been largely driven by government guidance and regulations [14]. China Construction Association (2021) also reported that for construction companies, the requirements of clients are the biggest driver for the use of BIM. The Chinese government has introduced both mandatory and incentive policies for the implementation of BIM. The former requires that the government projects with a building area of more than a certain square meter must use BIM, while the latter requires clients to set appropriate bonus points for bidders who commit to using BIM. However, the development of BIM in China is still hampered by insufficient government guidance. Although some policies and regulations have been introduced in China, the construction industry still wants more guiding standards adapted to the Chinese context, such as design standards, document delivery standards, and tariff standards [15]. Lack of policy is still the biggest issue preventing owners from using BIM [16–18].

In Pakistan, the implementation of BIM is slow [19]. A survey of Sindh, the province with the highest BIM usage and the largest population in Pakistan, shows that only 11% of related industries had implemented BIM, and BIM is limited to 3D modelling for large projects [2, 20]. Several surveys showed that Pakistani professionals are willing to implement BIM, but the major obstacle of lacking skills is hindering the development of BIM in Pakistan [19–22].

In Nigeria, BIM technology is relatively lagging, and the awareness of BIM is low [23, 24]. This is supported by the survey of Anifowose *et al.*, which found that only 40% of construction professionals were aware of BIM [25]. The Nigerian housing development board does not have incentive policies for BIM, but the local educational institutions have undertaken initiatives to add BIM courses to university architecture curricula to enhance graduates' BIM application skills [26]. BIM technology in Nigeria is mainly used in the design phase to produce drawings [27]. Engineers' lack of mastery of BIM technology is the main obstacle to BIM implementation in Nigeria [25, 26].

In Indonesia, BIM was first documented in 2013. Research on BIM was limited at the time and progressed slowly until it came alive in 2018 [28]. After formally introducing BIM in Indonesia in 2017, the Indonesian government developed a roadmap for BIM implementation and formed a BIM team to accommodate the process of BIM adoption in Indonesia [29]. However, the awareness of BIM in Indonesia was still in its infancy. Larasati *et al.* found that, in Indonesia, BIM was still perceived as a technology rather than an integrated system, resulting in the use of BIM not being collaborative among stakeholders [30]. A report by Sopaheluwakan *et al.* also shows that only a small number of survey respondents are able to use BIM. Most people only have a basic understanding of BIM or have only heard about BIM [29].

4. Discussion

The result shows that awareness campaigns can raise awareness of BIM, but they are not effective in increasing the BIM usage rate. In the literature review, all governments are aware of the importance of BIM to the sustainable development of the construction industry and have undertaken activities to promote BIM, such as adding BIM courses to universities and promoting BIM at industry conferences. But the generally low rate of BIM implementation in developing countries suggests that these non-mandatory promotional activities have not been effective in increasing BIM usage. Moreover, high BIM awareness does not directly lead to a high BIM usage rate. From the literature review, it is found that BIM awareness is high in India and Pakistan, but the BIM usage rates in these two countries are not significantly higher than those in Malaysia and Nigeria, two countries with low BIM awareness among construction professionals. This suggests that for developing countries, increasing BIM awareness alone is not effective in increasing the use of BIM. BIM implementers in the road construction sector in developing countries need to consider a comprehensive range of factors such as awareness, skills, education, benefits, and legislation.

Moreover, the development of appropriate BIM policies is a key long-term issue for BIM implementation in developing countries. Even in China, where mandatory policies are in place and BIM usage is high, the survey shows that the main obstacle to BIM implementation is still the lack of adequate policy support [11, 31]. However, there is a need to consider whether relying solely on government support for BIM implementation may make the industry overly dependent on policy support.

Furthermore, it is important to note that the adoption of mandatory policies in developing countries requires a gradual approach based on local realities. Due to differences in construction culture and legal systems, policies in other systems may not be adapted to the local road construction industry, despite their maturity. In China, for example, government-issued policies are very binding and driven, while in more market-oriented countries such as the UK and Malaysia, visible cost-effectiveness may have a greater driving force.

Whereas in India, where the economic system has the nature of both socialism and capitalism, the context of the construction industry will again be different. The BIM implementation sector needs to introduce localized policies to suit local circumstances.

5. Conclusion

This study explored the possibility of applying BIM in road construction within developing countries by reviewing a wide range of existing research. It focused on the main challenges and the reasons behind them. The results show that, although awareness campaigns have increased knowledge of BIM, they have not led to much use in practice. High awareness does not always bring high adoption because of several limits, such as a lack of technical skills, unclear economic gains, and weak policy support.

These findings suggest that developing countries should take a combined approach to encourage BIM adoption. This should include raising awareness, offering targeted training, providing economic support, and creating rules that match local building practices and legal systems. Policy decisions should be gradual and based on local conditions, rather than directly copying other countries' models. By combining technical standards, human resource development, and policy support, developing countries can create a better environment for BIM adoption, improve project efficiency, and promote sustainable growth in the construction sector

Disclosure statement

The authors declare no conflict of interest.

Author contributions

Writing original draft, Methodology, Conceptualization: Shuxing Kang
Writing-review and editing: Jia Wu

References

[1] Ullah K, Lill I, Witt E, 2019, An Overview of BIM Adoption in the Construction Industry: Benefits and Barriers. 10th Nordic Conference on Construction Economics and Organization, Emerald Publishing Limited, 2019: 297–303.

[2] Bhatti I, Abdullah A, Nagapan S, et al., 2018, Implementation of Building Information Modeling (BIM) in Pakistan Construction Industry. Eng. Technol. Appl. Sci. Res., 8(4): 3199–3202.

[3] Haron N, Soh R, Harun A, 2017, Implementation of Building Information Modelling (BIM) in Malaysia: A Review. Pertanika J. Sci. Technol., 25(3): 661–674.

[4] Harris M, Ismail E, Hussain A, 2015, Business Value of BIM In Malaysia's AEC Industry: Preliminary Findings. Malays. Constr. Res. J., 16(1): 31–41.

[5] Othman I, Al-Ashmori Y, Rahmawati Y, Mugahed Amran Y, Al-Bared M, 2021, The Level of Building Information Modelling (BIM) Implementation in Malaysia. Ain Shams Eng. J., 12(1): 455–463.

[6] Azmi N, Chai C, Chin L, 2017, Building Information Modeling (BIM) in Architecture, Engineering and Construction (AEC) Industry: A Case Study in Malaysia. Proceedings of the 21st International Symposium on Advancement of Construction Management and Real Estate, 2017: 401–412.

[7] Sawhney A, 2014, State of BIM Adoption and Outlook in India. RICS School of Built Environment, Amity

University, North Carolina.
[8] Charlesraj V, Dinesh T, 2020, Status of 4D BIM Implementation in Indian Construction. Proceedings of the 37th International Symposium on Automation and Robotics in Construction (ISARC), Tokyo, Japan.
[9] Mahalingam A, Yadav A, Varaprasad J, 2015, Investigating the Role of Lean Practices in Enabling BIM Adoption: Evidence from Two Indian Cases. J. Constr. Eng. Manag., 141(7): 05015006.
[10] Singhal N, Ahuja R, 2018, Can BIM Furnish Lean Benefits – An Indian Case Study. 26th Annual Conference of the International Group for Lean Construction, Chennai, India, Jul. 2018: 90–100.
[11] Xie M, Qiu Y, Liang Y, Zhou Y, Liu Z, Zhang G, 2022, Policies, Applications, Barriers and Future Trends of Building Information Modeling Technology for Building Sustainability and Informatization in China. Energy Rep., 8: 7107–7126.
[12] China Construction Industry Association, 2021, China Construction Industry BIM Application Analysis Report (2021). China Architecture Publishing & Media Co. Ltd., Beijing.
[13] Ministry of Housing and Urban-Rural Development, 2019, Notice on Submitting the Progress of the Project Quality and Safety Improvement Actions on a Quarterly Basis, China.
[14] Yang J, Chou H, 2018, Mixed Approach to Government BIM Implementation Policy: An Empirical Study of Taiwan. J. Build. Eng., 20: 337–343.
[15] Zhou Y, Zheng S, Liu Z, et al., 2020, Passive and Active Phase Change Materials Integrated Building Energy Systems with Advanced Machine-Learning Based Climate-Adaptive Designs, Intelligent Operations, Uncertainty-Based Analysis and Optimisations: A State-of-the-Art Review. Renew. Sustain. Energy Rev., 130: 109889.
[16] Huang B, Lei J, Ren F, et al., 2021, Contribution and Obstacle Analysis of Applying BIM in Promoting Green Buildings. J. Clean. Prod., 278: 123946.
[17] Zhou Y, Yang Y, Yang J, 2019, Barriers to BIM Implementation Strategies in China. Eng. Constr. Archit. Manag., 26(3): 554–574.
[18] Chen Y, Cai X, Li J, et al., 2022, The Values and Barriers of BIM Implementation Combination Evaluation Based on Stakeholder Theory: A Study in China. Eng. Constr. Archit. Manag., 2022.
[19] Siddiqui F, Akhund M, Ali T, et al., 2019, Barriers in Adoption of Building Information Modeling in Pakistan's Construction Industry. Indian J. Sci. Technol., 12(25): 1–7.
[20] Akdag S, Maqsood U, 2019, A Roadmap for BIM Adoption and Implementation in Developing Countries: The Pakistan Case. Archnet-IJAR Int. J. Archit. Res., 14(1): 112–132.
[21] Masood R, Kharal M, Nasir A, 2014, Is BIM Adoption Advantageous for Construction Industry of Pakistan. Procedia Eng., 77: 229–238.
[22] Hussain M, Memon A, Bachayo A, 2022, Building Information Modelling in Construction Industry of Pakistan: Merits, Demerits and Barriers. J. Appl. Eng. Sci., 12(1): 43–46.
[23] Saka A, Chan D, 2019, A Global Taxonomic Review and Analysis of the Development of BIM Research Between 2006 and 2017. Constr. Innov., 19(3): 465–490.
[24] Onungwa I, Uduma-Olugu N, Igwe J, 2017, Building Information Modeling as a Construction Management Tool in Nigeria. WIT Trans. Built Environ., 169: 25–33.
[25] Anifowose M, Sunday B, Olanrewaju O, 2018, Adoption Level of Building Information Modelling by Selected Professionals in Kwara State. Environ. Technol. Sci. J., 9(2): 35–44.
[26] Olanrewaju O, Chileshe N, Babarinde S, et al., 2020, Investigating the Barriers to Building Information Modeling (BIM) Implementation Within the Nigerian Construction Industry. Eng. Constr. Archit. Manag., 27(10): 2931–2958.
[27] Banawi A, 2017, Barriers to Implement Building Information Modeling (BIM) in Public Projects in Saudi Arabia. Advances in Intelligent Systems and Computing, 2017: 119–125.

[28] Telaga A, 2018, A Review of BIM (Building Information Modeling) Implementation in Indonesia Construction Industry. IOP Conference Series: Materials Science and Engineering, 2018: 012030.

[29] Sopaheluwakan M, Adi T, 2020, Adoption and Implementation of Building Information Modeling (BIM) by the Government in the Indonesian Construction Industry. IOP Conference Series: Materials Science and Engineering, Surabaya, Indonesia.

[30] Larasati D, Willis F, Hanifah Y, et al., 2018, Factors that Affect Maturity Level of BIM Implementation in Indonesia; Case Studies of 5 Construction Key Actors. 52nd International Conference of the Architectural Science Association, 2018: 673–681.

[31] Tan T, Chen K, Xue F, et al. 2019, Barriers to Building Information Modeling (BIM) Implementation in China's Prefabricated Construction: An Interpretive Structural Modeling (ISM) Approach. J. Clean. Prod., 219: 949–959.

Journal of Architectural Research and Development, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Experimental Study on Shear Mechanical Properties of Light Composite Bridge in Bending Moment Zone

Han Zhang*, **Shuwen Deng**

School of Water Resources and Civil Engineering, Agricultural University of Hunan, Changsha 410128, Hunan, China

**Author to whom correspondence should be addressed.*

Abstract: This study conducted shear resistance tests on steel-UHPC composite beams, focusing on structural stiffness changes during the test process, strain analysis of UHPC panels, internal reinforcement bars, steel structures, and shear connectors, as well as the failure processes and modes of UHPC panels and the structure. Through theoretical analysis, the contribution of UHPC panels to the overall vertical shear resistance capability was clarified. A shear load-bearing capacity calculation method was established, thereby considering the combined beam shear bearing capacity calculation formula of the UHPC panel and the steel beam web.

Keywords: Steel-UHPC composite beam; Positive moment zone; Shear resistance test; Bridge design theory and calculation method

Online publication: September 26, 2025

1. Introduction

Prefabricated composite bridge structures represent a crucial pathway for industrializing bridge construction [1]. However, traditional prefabricated bridges face two major challenges: (1) Bridges using conventional concrete materials are prone to cracking during operation, leading to water infiltration and durability issues; (2) Although beams can be manufactured in factories, on-site processes like welding assembly, prestressing installation, and shear wall pouring still require extensive time, causing significant traffic. Current research on the shear resistance of steel-UHPC composite beams predominantly focuses on lightweight composite deck structures, emphasizing longitudinal shear performance of shear connectors like anchors. However, studies on vertical shear resistance remain scarce. Research indicates that UHPC's inherent steel reinforcement provides significant shear strength. Zhu *et al.* [2] conducted experimental studies on vertical shear performance of steel-UHPC waffle plate composite beams, revealing that the web section contributes only about 50% to overall shear resistance, while the UHPC flanges play a crucial role. Consequently, using code-specified methods that account solely for web strength when calculating shear capacity under steel-UHPC composite beams would result in overly conservative estimates.

Notably, load-bearing conditions for these composite beams differ from conventional concrete structures in terms of effective lateral width, shear calculation methods, and transverse-bending load-bearing capacity assessment approaches [3].

In short, this study employs a combination of experimental research and theoretical analysis to investigate the fundamental mechanical behavior of shear resistance in the positive bending moment zone of light composite bridges. Building on these findings, we aim to elucidate the synergistic load-sharing mechanisms during service and propose corresponding design theories and computational methods. The research constitutes a crucial component of composite bridge system design theory, with its outcomes contributing to enhanced bridge systems in the future.

2. Study overview

The test girders are shown in **Figure 1**. All girders measure 4.30 meters in length with a clear span of 4.0 meters. The UHPC panels are 700 mm wide and 65 mm thick, featuring longitudinal and transverse reinforcement bars of HRB400 grade (Hot-Rolled Ribbed Bars, yield strength ≥400 MPa). The reinforcement system consists of longitudinal bars (LR: 7Φ16 mm) and transverse bars (TR: Φ12@100 mm). The I-beam girders, constructed from Q345 steel (yield strength ≥345 MPa), have a total height of 440 mm with a top flange measuring 140 mm × 6 mm and a bottom flange measuring 250 mm × 10 mm. The web is 8 mm thick, and Φ16×50 mm shear connectors are used to bond the UHPC panels to the I-beam girders.

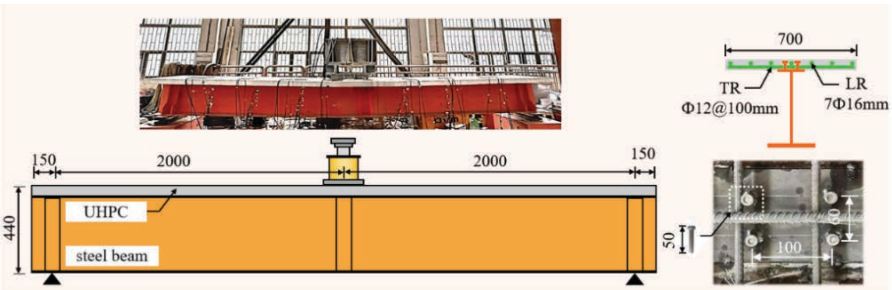


Figure 1. Test beam profile (unit: mm)

The hydraulic jack was used to apply loading to the test beam. As shown in the figure above, this experiment employed a three-point loading method. Both ends of the test beam were mounted on a steel platform: one end was equipped with a movable hinge bracket for free sliding, while the other had a fixed hinge bracket to restrict lateral movement. The three-point loading configuration directly positioned the jack precisely above the beam's mid-point.

The UHPC material used in this test is a commercial dry powder (Xingguli), with primary components including cement, quartz powder, high-efficiency water reducer, and steel fibers (8 mm × 0.12 mm straight steel fibers, 2% by volume). The testing methods for compressive strength, flexural strength, and elastic modulus of the UHMPC material follow GB/T 31387-2015. The fundamental mechanical properties of the UHMPC are summarized in Table 1. The lower steel structure of the test beam employs Q345 steel, while the UHMPC panel uses HRB400 grade reinforcement. The material properties of steel plates and reinforcement are determined through performance testing, with a Poisson's ratio of 0.3. The mechanical properties of the steel are detailed in Table 2.

Table 1. Mechanical properties of UHPC materials

Curing condition	Compression strength (MPa)	Rupture strength (MPa)	Modulus of elasticity (GPa)
Steam-cured	139.8	24.6	45.1

Table 2. Mechanical properties of steel

Material	Yield strength (MPa)	Ultimate strength (MPa)	Modulus of elasticity (GPa)
6 mm (steel plate)	394.3	525.6	
8 mm (steel plate)	390.4	545.2	206
10 mm (steel plate)	363.7	498.4	
Reinforcing bar	466.7	572.4	200
Steel beam	350	/	200

3. Results and discussion

3.1. Destruction process and mode

After completing the tests, the failure process can be categorized into four distinct phases based on observed phenomena and results. Phase I: Initial Synergy Stage. During the initial loading phase, all test beams demonstrated effective joint performance. When the load reached approximately 400 kN, audible "squeaking" noises were detected as steel fibers were extracted from the UHMPC matrix. Microscopic cracks appeared at the steel-UHMPC interface near the loading point.

Among them, the ultimate load of the test beam is 917 kN. At this time, an obvious slip occurs between the upper edge of the steel beam and the bottom of the UHPC panel. The observed strain shows that both the upper and lower edges reach the yield value (394.3 MPa / 206 GPa = 1914), that is, the test beam reaches the full section yield of the steel beam when it breaks.

3.2. Load-displacement response

The deformation of the test beam with the development of the load was tested, and the load-span deflection curve is drawn as shown in **Figure 2**.

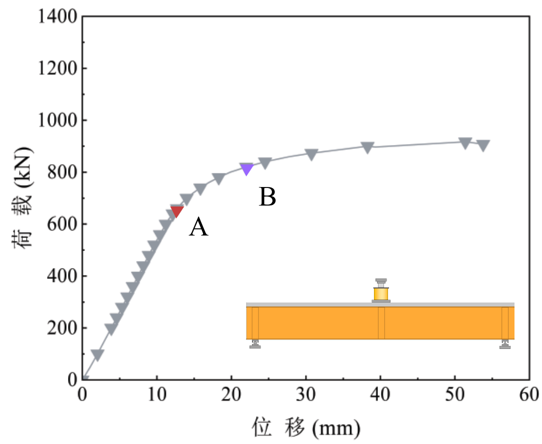


Figure 2. Test load-deflection curve at mid-span

As can be seen in **Figure 2**, the load-deflection curve of the test beam basically changes in the same way, which can be roughly divided into three stages: elastic stage, elastoplastic stage, and failure stage.

Phase I: Elastic Stage (O~A). During this phase, the beam stiffness is provided by both the steel beam and the UHPC panel. The specimen exhibits relatively straight load-displacement curves, indicating structural compliance. Phase II: Elastoplastic Stage (A~B). As loading intensifies, the curve develops deflection. Near the loading point, numerous transverse cracks appear at the bottom of the UHPC panel and gradually penetrate through. Simultaneously, localized buckling occurs in the steel beam flanges, leading to reduced stiffness, accelerated deflection growth, and a steeper slope in the curve. Phase III: Failure Stage (B~C). At this stage, the lower edge of the composite beam's steel section reaches yield strain while the upper UHPC panel collapses. Significant mid-span deflection occurs, reaching the ultimate load, where further loading becomes impossible. The displacement growth rate intensifies, prompting termination of the test.

3.3. Load-strain response

To investigate the longitudinal strain of UHPC panels across mid-sections under load variations and the transverse strain along the width direction on the top surface of the same section, we plotted the surface strain changes of the experimental beam's UHPC panel as shown in Figure 3. The figure reveals that the strain growth rate at the central axis (EUn2) of the bridge deck plate increases more rapidly with greater amplitude, while the edge positions (EUn1 and EUn3) show relatively slower strain progression and smaller deformation ranges. This indicates a "lagged release" of shear force in the central region or "delayed response" at the edges, meaning the central axis area bears more longitudinal deformation while the shear force fails to fully extend laterally to the periphery.

For further analysis, the shear lag coefficient of the experimental beam was calculated using the formula (mid/edge), where mid represents the strain at the panel's center (e.g., EUn2) and edge denotes the strain at the panel's edge (e.g., EUn1/3). The calculated shear span ratio of the experimental beam was 3.96. Under concentrated loading at mid-span, the central axis strain was significantly higher than that in the edge region (up to 1.75), indicating a severe shear lag effect. This demonstrates that concentrated loading is more likely to cause stress concentration and limit shear diffusion.

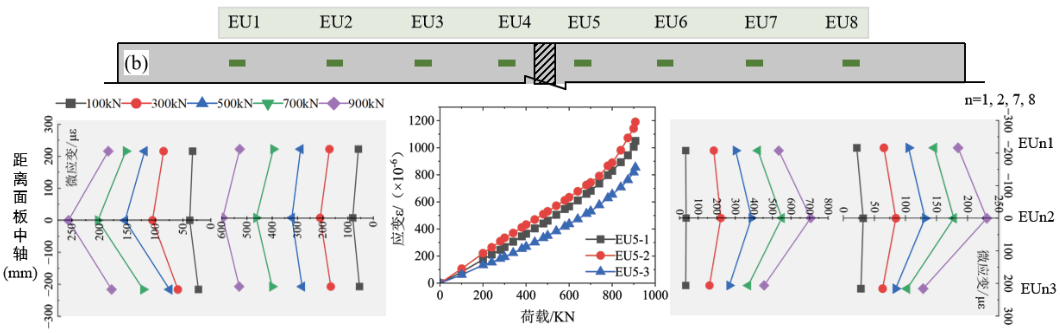


Figure 3. Strain of test beam panels

4. Calculation of shear bearing capacity

Current international standards for calculating shear resistance in steel-concrete composite beams exclude concrete flange contributions, assuming all vertical shear forces are borne solely by the steel web. However, literature analysis reveals that concrete flanges significantly enhance shear performance, with more pronounced improvements as concrete strength increases. This study emphasizes the critical role of UHMWPE (Ultra-High Molecular Weight Polyethylene) concrete in steel-UHMPE composite beams. Employing the superposition principle, we develop a composite beam shear resistance calculation formula that incorporates both UHMWPE concrete panels and steel web elements.

The shear bearing capacity of the I-beam, according to China's "Code for Design of Steel Structures" (GB50017-2003), only considers the shear resistance of the steel beam's web as the contribution of the steel beam's shear resistance.

$$V_s = f_{sy} h_w t_w \sqrt{3}$$

In the formula, *f* is the yield strength of the steel beam web, and *h*, *t* are the height and width of the steel beam web, respectively. Substituting the experimental values yields the shear contribution of 764.5 kN of the steel beam.

The shear bearing capacity of UHPC panels is calculated by referring to the calculation formula proposed in the French UHPC structural design code [4], which is mature and has been widely used.

The UHPC section of the reinforcement is calculated according to the following formula.

$$V_c = \frac{0.21}{\gamma_{cf} \gamma_E} k_N {f_{ck}}^{0.5} b h_0$$

In the formula, ***b*** represents the width of the rectangular cross-section; UHPC is the effective height of the rectangular section; the coefficients are the load or prestress enhancement factor (set to 1.5), and UHPC denotes the partial coefficient for tensile materials and safety factor, respectively (both set to 1.5). Substituting these values into the calculation yields a shear contribution value of 113 kN for the UHPC panel. Based on the combined formulas, the shear load-bearing capacity of the composite beam using the superposition principle is calculated as follows:

$$V_u = V_c + V_s$$

Substituting the above formula, it can be calculated that 877.5 kN is close to the experimental result of 917 kN with an error of 4.3%. The contribution value of the UHPC panel to the shear bearing capacity of the composite beam is 13%.

5. Conclusion

This paper studied the basic mechanical properties of shear resistance in the bending moment zone of light composite beams and drew the following conclusions:

(1) The test beam is a three-point loaded specimen. Under the centralized loading at the mid-span, the strain of the central axis is significantly higher than that of the edge region (up to 1.75, showing an extremely serious shear lag effect. Centralized loading is more likely to cause stress concentration and shear diffusion limitation.

(2) For the calculation of the shear bearing capacity of the test beam, the superposition principle is used to consider the combined beam shear bearing capacity calculation formula of the UHPC panel and the steel beam web. The comparison results show that the shear bearing capacity calculation formula proposed in this paper has higher accuracy.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Zhang Z, Deng K, Xu T, 2020, Research Progress on Prefabricated Concrete Bridge Structures in 2019. Journal of Civil and Environmental Engineering: Chinese and English Edition, 221(05): 187–195.

[2] Shao X, Zhang H, Li J, et al., 2020, Study on Shear Resistance of Steel-Ultra-Thin UHPC Lightweight Composite Bridge Deck Short Reinforcement Connectors. Journal of Civil Engineering, 53(1): 39–51.

[3] Zhu J, Wang Y, Guo X, et al., 2020, Study on Shear Resistance Performance of Steel-UHPC Corrugated Composite Beams. Journal of Highway Science and Technology, China, 33(11): 169.

[4] AFGC-SETRA, 2016, National Addition to Eurocode 2-Design of Concrete Structures: Specific Rules for Ultra High Performance Fibre-Reinforced Concrete (UHPFRC). AFNOR, 2016: 99–121.

Journal of Architectural Research and Development, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Discussion on the Inspection Standards of Construction Quality for Office Buildings

Liang Chen*

Shenzhen 518000, Guangdong, China

**Author to whom correspondence should be addressed.*

Abstract: This paper introduces the relevant content of construction quality inspection standards for office buildings, including their differences and special requirements of general buildings. It elaborates on the application of BIM technology and the PDCA cycle model in each stage of construction, emphasizes the importance of technical management system construction, and also discusses the influence and optimization path of prefabricated buildings and LEED certification on the standards.

Keywords: Office building; Construction quality; Inspection standard

Online publication: October 10, 2025

1. Introduction

In the context of the development of the construction industry, the construction quality inspection standards for office building projects cover core elements such as the quality of the project entity, material quality, and construction process standardization. The particularity of office buildings requires unique requirements in terms of structural safety, fire protection systems, and intelligent configuration, which require targeted analysis. During the construction phase, it is extremely important to implement inspection standards by combining BIM technology, the PDCA cycle model, and a technical management system. BIM technology assists in full lifecycle management, the PDCA cycle promotes continuous quality improvement, and the technical management system provides standardized operating procedures and quality control basis. At the same time, the standardization of the engineering planning stage lays the foundation for optimizing inspection standards, clarifying quality objectives and inspection points, providing guidance for quality control in the construction process, and ensuring high-quality delivery of office building projects.

2. Basic theory of quality inspection standards for office building construction projects

2.1. Definition and classification of construction quality inspection standards

The construction quality inspection standard is a technical document that specifies the characteristics and indicators of construction quality, used to measure whether the construction quality meets the requirements. It covers all aspects of engineering construction, including the quality of materials, components, equipment, construction technology, quality control during the construction process, and acceptance after project completion. From a hierarchical perspective, it can be divided into national standards, industry standards, and enterprise standards. National standards are authoritative and mandatory standards formulated by relevant national departments, and are the basic requirements that must be met for the quality of construction projects. Industry standards are standards developed by industry associations or organizations, which supplement and refine national norms and are more targeted and professional. Enterprise standards are standards formulated by enterprises based on their own technical level and management requirements, usually stricter than national norms and industry standards, and are an important means for enterprises to improve their competitiveness [1].

2.2. Special requirements for office building engineering

As a specific type of building, office buildings have their own particularities compared to residential and industrial park factories, which determine their unique requirements for construction quality inspection standards. In terms of structural safety, office buildings often have more floors and carry heavier personnel and equipment, requiring higher strength and stability of the foundation and main structure [2]. The fire protection system plays a crucial role in office buildings. Due to the high density of personnel and the numerous office equipment, there are significant fire hazards. Therefore, the quality standards for the provision of fire protection facilities, fire separation, evacuation routes, and other aspects are more stringent. Intelligent configuration is also an important feature of office buildings, which needs to meet the needs of efficient office work, including quality inspection standards for intelligent security, intelligent lighting, intelligent communication, and other systems. The special requirements of these office building projects require the development of targeted standards during construction quality inspection.

3. Specific applications of inspection standards in the construction phase

3.1. Standard execution in the dimension of technical management

The application of BIM technology is extremely important for the implementation of inspection standards during the construction phase [3]. In terms of concealed engineering acceptance, utilizing the visualization characteristics of BIM technology, virtual modeling and analysis of concealed engineering can be carried out before construction, and the acceptance points and standards can be determined in advance. During the construction process, strict adherence to standard procedures is required, such as pipeline laying and cable embedding for concealed works. After completing the corresponding construction stages, timely acceptance checks are conducted against BIM models and established standards. For material quality testing, it is necessary to conduct a comprehensive evaluation using advanced testing equipment and technology in accordance with relevant standards. When materials enter the site, not only should their strength be tested, but also their specifications, performance, durability, and other indicators should be checked to ensure compliance with engineering requirements. BIM technology can be used for material information management by establishing a material database to record information such as material sources, specifications, and testing reports, achieving traceability and management of the entire life cycle of materials. At the same time, BIM models can be associated with detection data to update material status in real-time, providing data support for construction quality control and ensuring the construction quality of office building projects.

3.2. Integration of quality control in progress management

During the construction phase, the collaborative management of the construction schedule and quality inspection nodes is achieved through the PDCA cycle model [4]. In the planning (Plan) phase, a detailed construction schedule plan including quality inspection nodes is developed based on the characteristics of the office building project, clarifying the quality objectives and inspection standards for each stage. During the implementation (Do) phase, strictly follow the construction plan and carry out quality inspection work synchronously to ensure that the quality of each inspection node meets the standards. During the checking (Check) phase, compare the quality of actual progress with planned goals and promptly identify deviations. In the action (Act) phase, adjustment measures are taken to analyze the reasons for deviations, such as rectifying parts that do not meet quality standards, optimizing subsequent construction schedules and quality inspection node arrangements, and achieving dynamic integration and continuous improvement of schedule management and quality control.

4. Impact mechanisms of technical management on inspection standards

4.1. Construction of the technical management system

4.1.1. Preparation of standardized work instructions

The construction of a technical management system is extremely important in the quality inspection standards for office building construction [5]. It covers all aspects from construction technology to quality control. By establishing a comprehensive technical management system, the responsibilities of each department and personnel are clarified, ensuring the standardization and normalization of the construction process. The preparation of standardized work instructions is a key part. It specifies in detail the various steps and operating standards of construction, providing clear guidance for construction personnel. This helps to reduce human errors during the construction process and improve construction quality. At the same time, the homework manual should be compiled based on the visual disclosure of construction process standards to ensure its close integration with the actual construction process. Visual disclosure of construction process standards plays a core role in quality pre-control, as it enables construction personnel to have a more intuitive understanding of construction requirements and quality standards, thereby better ensuring that construction quality meets inspection standards.

4.1.2. Technological innovation in testing equipment

The construction of a technical management system has a significant impact on inspection standards. Reasonable technical management can ensure the accuracy and reliability of testing equipment, thereby providing strong support for inspection standards. In terms of technological innovation in detection equipment, taking the application of intelligent detection instruments in real-time monitoring of concrete strength as an example, technological innovation has made detection more accurate and efficient. Intelligent detection instruments can obtain real-time concrete strength data, which not only improves detection efficiency but also provides a more accurate data basis for the formulation of inspection standards. By guiding and standardizing the technological innovation of testing equipment through technical management, the inspection standards can be continuously optimized to make them more scientific and reasonable, and meet the actual needs of engineering construction quality [6].

4.2. Adaptation of new technology application standards

4.2.1. Optimization of construction standards for prefabricated buildings

The application of new technologies in prefabricated construction promotes the continuous adaptation and optimization of inspection standards. Taking prefabricated component connections as an example, with the improvement of technical management level, new connection technologies continue to emerge, such as new bolt connections, grouting sleeve connections, etc. [7]. The application of these new technologies requires updating the existing quality inspection standards. In terms of connection quality inspection, it is necessary to redefine key inspection indicators based on the characteristics of new technologies, such as connection strength, compactness, sealing, etc. At the same time, the inspection methods also need to be updated, which may involve the use of advanced non-destructive testing techniques to more accurately evaluate the quality of the connections. Technical management influences the quality inspection standards for prefabricated building components by promoting the application of new technologies, including inspection indicators and methods, in order to continuously optimize them to meet the development needs of the construction industry.

4.2.2. Upgrade of green construction technology standards

The LEED certification system, as an advanced green building evaluation standard, has a significant impact on the energy-saving and emission reduction testing indicators during the construction process of office buildings. It has promoted the transformation of technical management in terms of inspection standards, and facilitated the adaptation of new technology application standards and the upgrading of green construction technology standards. In terms of the application of new technologies, it is required that the new technologies used in the construction process must comply with the strict requirements of the LEED certification system for energy conservation and emission reduction, ensuring that the application of technologies can effectively improve energy utilization efficiency and reduce pollution emissions [8]. At the same time, the green construction technology standards have also been upgraded accordingly, such as placing more emphasis on environmental performance in material selection, stricter waste management during construction, and more refined energy consumption monitoring, in order to meet the high standard requirements of the LEED certification system for office building construction quality.

5. Integration of inspection standard optimization path and engineering planning

5.1. Standardization prerequisites in the engineering planning phase

5.1.1. Linkage between quality objectives and planning schemes

During the engineering planning phase, emphasis should be placed on standardization as a prerequisite, closely linking quality objectives with the planning scheme [9]. Establishing an engineering quality cost optimization model based on value engineering theory is crucial. In engineering planning, it is necessary to clarify quality objectives based on the characteristics and requirements of office building projects, which should cover multiple aspects such as building structural safety and functional improvement. At the same time, the planning scheme should revolve around quality objectives, from the selection of construction technology, material, and equipment to personnel organization and arrangement, all of which should be guided by ensuring the achievement of quality objectives. For example, in terms of construction technology, mature technology that has been verified through practice and meets relevant standards should be selected; in the selection of materials and equipment, attention should be paid to quality and performance to ensure that they meet the usage needs and quality standards of office buildings. Through this close linkage, standardization is achieved in the engineering planning stage, laying the foundation for optimizing the inspection standards of subsequent construction quality.

5.1.2. Construction of risk warning standard system

Standardization should be prioritized during the engineering planning phase. For the optimization of inspection standards for the construction quality of office buildings, the FMEA method can be used to develop construction quality risk classification and control standards, and to construct a risk warning standard system. By analyzing potential risks that may arise during the construction process, identifying potential failure modes and their influencing factors, assessing the severity, frequency, and detectability of risks, and determining the risk level. Develop corresponding control measures based on risk levels to effectively prevent and control construction quality risks. At the same time, incorporating these risk control standards and measures into project planning ensures that every aspect of the construction process meets quality requirements, improving the stability and reliability of office building construction quality [10].

5.2. Dynamic adjustment of standards driven by progress

5.2.1. Quality control standards for critical circuits

In terms of integrating engineering planning, it is necessary to incorporate inspection standards into the overall engineering planning process. From the initial stage of the project, set quality objectives and an inspection standard framework based on the characteristics of the office building project. As the project progresses, standards will be dynamically adjusted based on schedule-driven approaches. When the progress of processes on the critical path is advanced or delayed, adjust the frequency and focus of quality inspection accordingly. For the quality control standards of critical routes, it is necessary to determine the key processes. Study the method for determining the strength coefficient of key process quality inspection in network planning technology, and scientifically set the strength coefficient based on factors such as the importance, complexity, and impact on subsequent processes of the process. Reasonably arrange inspection resources based on this coefficient to ensure effective quality control on critical routes and guarantee the overall quality of office building projects.

5.2.2. Quality assurance standards under rush work conditions

In office building construction, inspection standards need to be integrated with project planning and dynamically adjusted according to progress. Quality assurance standards are extremely important in a rush-to-work state. Special clauses for parallel construction quality acceptance should be formulated under the condition of a compressed construction period. This requires a comprehensive consideration of the impact of rush work on various construction stages, and accurate identification and evaluation of potential quality risk points. For example, in areas where multiple job types are working simultaneously, clarify the quality responsibilities and acceptance standards of each job type to avoid the phenomenon of shirking responsibility. At the same time, strengthen the quality control of key processes and concealed works, increase inspection frequency and strictness. In terms of material usage, even during the rush stage, it is necessary to adhere to the quality standards of materials and avoid using unqualified materials due to schedule pressure. By implementing these measures, we ensure that the material quality is always under control, thereby guaranteeing the construction quality of the office building project while rushing to meet the deadline.

5.3. Collaborative innovation of multiple engineering types and standards

5.3.1. Transfer of experience in residential and factory engineering

The improvement plan for steel structure testing standards in office building projects can be considered from multiple aspects. In material testing, advanced technology is borrowed to ensure that the quality of steel meets the high strength and toughness requirements for office building projects. For the inspection of welding parts, based on the experience of factory engineering, various non-destructive testing methods are adopted to ensure the quality of welding, such as combining ultrasonic testing with radiographic testing to improve the accuracy of defect detection. In terms of overall structural stability testing, referring to the large-scale structural testing methods of factories, finite element analysis and other methods are used to simulate the stress situation of office buildings under different load conditions, ensuring the safety and reliability of the structure. Meanwhile, considering the functional characteristics of office buildings, the testing standards for fire prevention, sound insulation, and other aspects should be optimized based on factory engineering to meet the usage needs of office buildings.

5.3.2. Integration of smart construction site standard system

To achieve the integration of inspection standard optimization path and engineering planning, as well as collaborative innovation of multiple types of engineering standards, it is necessary to construct a unified standard framework for IoT quality monitoring applicable to multi-format engineering. This framework should integrate the characteristics and requirements of different types of engineering, breaking the limitations of traditional standards. Through IoT technology, real-time monitoring and data collection of engineering quality can be achieved, providing an accurate basis for quality assessment. At the same time, it is necessary to closely integrate all aspects of engineering planning with inspection standards to ensure that every step of the construction process meets quality requirements. In terms of integrating the standard system of smart construction sites, advanced technologies such as the Internet of Things, big data, and artificial intelligence should be fully utilized to achieve interconnectivity and intelligent management of construction site information, improve engineering quality and management efficiency, and promote the improvement of construction quality in office buildings.

6. Conclusion

The construction quality inspection standards for office building projects cover multiple core elements. From the perspective of engineering entity quality, it includes indicators such as stability and safety of building structures, as well as aesthetic and practical standards for decoration projects. Material quality inspection is also crucial, ensuring that the materials used comply with relevant specifications. Meanwhile, the standardization and rationality of construction techniques are equally important.

With the development of technology, BIM + 5G technology provides direction for intelligent inspection standards. Real-time and accurate quality monitoring and data transmission can be achieved through the visualization model of BIM and high-speed transmission of 5G.

Standard pre-control during the engineering planning phase is of great significance for quality management throughout the entire lifecycle. It can plan quality objectives and control measures in advance, avoid quality problems during the construction process, ensure that office building projects meet high-quality requirements from start to delivery, and improve the overall quality level of the project.

Disclosure statement

The author declares no conflict of interest.

References

[1] Hou Z, 2020, Research on Optimization of Property Service Management in F Company's Office Building, dissertation, Central South University of Economics and Law.

[2] Yu C, 2020, Research on Fine Quality Management Evaluation and Improvement of an Office Building Mechanical and Electrical Installation Project, dissertation, Beijing Jiaotong University.

[3] Shan C, 2019, Research on Security Risk Management in Office Building Property Management—Taking a State-Owned Enterprise Office Building Property Project as an Example, dissertation, University of the Chinese Academy of Sciences.

[4] Zhao J, 2017, Research on Quality Evaluation and Application of Property Management Services in Office Buildings.

Technological Innovation and Productivity, (12): 37–39.
[5] Han C, 2014, Employee Mobility Management in Office Property Enterprises: A Case Study of Beijing R Office Property Enterprise, dissertation, Capital University of Economics and Business.
[6] Lou J, Liu H, Ye Y, et al., 2015, Research and Application of Testing Technology for Clay Concrete Impermeable Wall. Sichuan Hydroelectric Power, 34(06): 164–168 + 179.
[7] Wang J, 2022, Thoughts on the Inspection Method and Standard of Baijiu. Food Safety Guide, (29): 171–173.
[8] Gao J, 2023, Discussion on the Inspection Standards and Methods of Baijiu. Food Safety Guide, (03): 55–57.
[9] Wu J, Yang W, 2014, Discussion on the Net Content and Inspection Rules of Quantitative Packaging for Toilet Paper Products. Science and Technology Innovation and Application, (20): 292.
[10] Zou Z, 2019, Exploration of Inspection Standards for Forklifts and Problems in Actual Inspection. Science and Technology Innovation Report, 16(12): 76–77.

Journal of Architectural Research and Development, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Research on Multi-Dimensional Collaborative Strategies in Design Management, Investment Management, and Beyond from the Perspective of Whole-Process Engineering Consulting

Zexin Chen*

Shenzhen 518000, Guangdong, China

**Author to whom correspondence should be addressed.*

Abstract: This paper explores whole-process engineering consulting, including its application models in public buildings and elderly-friendly projects, such as service integration and whole lifecycle management. It also addresses the construction of multi-dimensional collaborative theoretical models, public space streamline organization, and other aspects, emphasizing the importance of multi-dimensional collaboration. Additionally, it highlights the role of talent cultivation and digital transformation in enhancing project efficiency.

Keywords: Whole-process engineering consulting; Multi-dimensional collaboration; Project efficiency

Online publication: October 10, 2025

1. Introduction

With the development of the construction industry, the whole-process engineering consulting model has garnered increasing attention. The *2017 Opinions of the General Office of the State Council on Promoting the Sustainable and Healthy Development of the Construction Industry* proposed fostering whole-process engineering consulting, providing policy support for its advancement. This model encompasses multiple core elements, including service integration and whole lifecycle management, demonstrating significant advantages in public buildings and elderly-friendly projects by enhancing comprehensive benefits and reducing costs. Simultaneously, it involves multi-dimensional collaboration—such as collaboration between design management and investment control—while requiring attention to the application of intelligent sensing technologies and digital transformation pathways to better adapt to industry development needs.

2. Theoretical framework and practical characteristics of whole-process engineering consulting

2.1. Analysis of the whole-process engineering consulting model

The whole-process engineering consulting model covers multiple core elements. Among them, service integration is crucial. It integrates consulting services of different stages and professions, breaks the fragmentation of traditional consulting services, and realizes the continuity and synergy of consulting services. For example, in public building design, design management and investment management are no longer isolated but closely connected through service integration. The concept of whole-lifecycle management runs through the entire process, and all aspects from the early planning to the later operation and maintenance of the project are included in the consulting scope. In public building design, this means considering various links such as investment estimation in the early stage of architectural design, cost control during the construction process, and cost-benefit analysis in the operation stage. This model helps improve the comprehensive benefits of the project, reduce resource waste, and enhance the overall quality and sustainability of the project [1].

2.2. Construction of a multi-dimensional collaborative theoretical model

In administrative service center projects, there are differences in the implementation of the "Code for Accessible Design." Through comparative analysis of these differences, some key issues can be identified. The width of accessible passages in some areas does not meet the standard requirements, and wheelchairs are easily squeezed by facilities on both sides when passing through; in some projects, the location of accessible facilities is unreasonable. The installation height of emergency buttons exceeds the reach of wheelchair users, and there are right-angle turns at the junction of blind paths and elevator entrances, which bring multiple obstacles to the use of the disabled.

To improve this situation, parametric design tools can be applied. With this tool, a parameter model including passage width, facility spacing, handrail height, and other elements is established, and the numerical standards in the "Code for Accessible Design" are converted into design parameters that can be verified in real time. During the design process, the model can automatically detect non-conforming items and issue prompts to ensure that details such as passage width and facility location accurately meet the specification requirements. Parametric design tools can make accessible design naturally integrate with the overall style of the building. While ensuring that the slope of the ramp meets the standards, the material and shape of the ramp handrail can be adjusted to coordinate with the modern and simple style of the administrative service center. This method improves design efficiency on the basis of meeting accessible design standards, enabling public buildings to enhance overall functionality and applicability while ensuring the convenience of use for special groups [2].

3. Research on collaborative strategies for public building design

3.1. Key points of function-oriented design management

3.1.1. Strategies for organizing public space circulation

The organization of public space circulation is a key element in public building design. In function-oriented design management, it is necessary to fully consider the flow patterns and usage needs of pedestrian traffic. Taking a civic cultural center project as an example, pedestrian flow simulation technology has played an important role. For functionally complex buildings such as theaters and exhibition halls, their floor plans are intricate with frequent pedestrian crossings. Through pedestrian flow simulation technology, it is possible to accurately capture the characteristics of pedestrian distribution in different time periods and under various activity scenarios, providing a scientific basis for optimizing the organization of public space circulation. For the pedestrian flow that pours out in a short time when a theater ends a performance, the optimal evacuation routes can be determined based on simulation data, and multi-directional passages can be designed in conjunction with the arrangement of seats to avoid congestion caused by a single circulation path. In exhibition hall areas, the spacing between display cabinets and visiting routes can be adjusted according to differences in pedestrian flow intensity for different exhibition themes, allowing the circulation of popular exhibition areas and regular exhibition areas to be naturally separated and reducing cross-interference. At the same time, the location distribution of entrances and exits can be optimized using simulation results, making the entrances and exits of different functional areas relatively independent while maintaining reasonable connections. This not only facilitates users to quickly reach their target areas but also balances the pedestrian flow in each passage. Through such circulation optimization based on actual usage scenarios, it is possible to enhance the sense of smoothness and comfort for users moving through the space, and also make the spatial layout of public buildings more in line with functional needs [3].

3.1.2. Implementation path of barrier-free design standards

In administrative service center projects, there are differences in the implementation of the Code for Barrier-Free Design. Through comparative analysis of these differences, some key issues can be identified. For example, the width of barrier-free passages in certain areas may not meet the standard requirements, or the location of barrier-free facilities may be unreasonably set, causing inconvenience to the disabled in their use [4]. To improve this situation, parametric design tools can be applied. Using such tools, various parameters of barrier-free design can be set more accurately, ensuring that passage width, facility location, and other aspects comply with standard specifications. Meanwhile, parametric design tools can also improve design efficiency. On the premise of meeting barrier-free design standards, they can better integrate with the overall architectural design, enhancing the functionality and applicability of public buildings.

3.2. Application of value engineering in investment management

3.2.1. Implementation framework of quota design

As an important means of investment management, quota design plays a key role in the collaborative design of public buildings. Its implementation framework should cover such links as target setting, design process control, and effect evaluation [5]. A reasonable cost quota is determined according to the project's investment estimation and functional requirements. This quota needs to balance the realization of the project's necessary functions and investment costs, and set a clear cost boundary for subsequent design work. In the design process, value engineering methods are used to optimize the scheme.

On the basis of ensuring that all functions meet the standards, the cost is controlled through adjusting material selection and optimizing structural forms, so as to avoid cost overruns caused by over-design or functional redundancy. The design team and the investment management team need to establish a close communication and coordination mechanism, timely exchange opinions on cost-sensitive points in the design scheme, and dynamically adjust design details according to investment feedback, so that the scheme meets functional standards without exceeding the cost quota. After the design is completed, a comprehensive evaluation of the implementation effect of quota design is carried out, the causes of deviations between the actual cost and the preset quota are analyzed, and effective experiences in design optimization and cost control are summarized. This provides a reference for quota design of similar projects and forms a virtuous cycle of continuous improvement.

3.2.2. Key points of whole-cycle cost control

In stadium projects, whole-cycle cost control is of vital importance. A dynamic cost database needs to be established to systematically collect cost information of the project at various stages. It covers data from the budget estimate in the design stage, the budget and settlement in the construction stage, to the energy consumption expenses and facility maintenance costs in the operation and maintenance stage. All these data are included in the collection scope, and through structured storage and classified sorting, accurate data support is provided for cost control in each link. On this basis, an operational model of design change and a claim early warning mechanism are constructed [6]. In the design stage, factors that may cause cost changes, such as fluctuations in material prices, adjustments to technical standards, and changes in geological conditions, are identified.

Combined with historical data, the impact of different factors on costs is simulated. When it is monitored that the design scheme has the risk of exceeding the cost threshold, or changes in construction conditions may lead to claims, the model automatically triggers an early warning, promoting the collaborative response of the design, construction, and cost management teams. By adjusting design parameters in a timely manner, optimizing construction schemes, or formulating claim response strategies in advance, pre-control of cost risks is realized. This whole-cycle dynamic management model can not only ensure the continuity and accuracy of cost data at all stages but also reduce the probability of cost out-of-control through the risk early warning mechanism, thereby improving the economic benefits and investment management level of stadium projects.

4. Collaborative innovation system for age-friendly living spaces

4.1. Construction of an age-friendly design standard system

4.1.1. Age-friendly design of physical environment

In terms of age-friendly design of physical environment, it is necessary to develop an age-friendly hierarchical evaluation system to conduct scientific assessment on bathroom spaces in elderly apartment projects. This system provides a quantifiable evaluation basis for age-friendly design by quantitatively analyzing the realization degree of safety design indicators in bathroom spaces, ensuring that all details meet age-friendly standards. The size planning of bathroom spaces should fully consider the range of the elderly's physical activities, reserving sufficient space for turning around and moving, so as to avoid accidents such as bumps or falls caused by cramped space [7].

Floor anti-slip measures need to be implemented in two aspects: not only selecting anti-slip materials with friction coefficients meeting standards, but also matching auxiliary facilities such as anti-slip mats and drainage grooves to reduce safety risks in wet and slippery environments. The height and shape of bathroom facilities should conform to the physical function characteristics of the elderly. For example, the height of toilet armrests is adapted to the support needs when sitting up, space for wheelchair knees is reserved under the washbasin, and lever-type handles are used for faucets to facilitate operation by elderly people with weak strength. Through the precise implementation of these design details, while meeting safety requirements, the convenience and comfort of the elderly during use are improved, making the physical environment truly adapt to the living needs of the elderly group.

4.1.2. Integration of intelligent health monitoring systems

In the collaborative innovation system for age-friendly living spaces, the integration of intelligent health monitoring systems is a key component. This system needs to combine Internet of Things (IoT) technology to realize the collaboration of subsystems such as emergency calls and environmental monitoring in elderly care communities. Through sensors and other devices, real-time collection of the elderly's health data and living environment information is conducted, such as heart rate, blood pressure, indoor temperature, and humidity [8]. Data analysis technology is used to process and analyze these data, so as to timely detect health problems and potential risks of the elderly. At the same time, the system should be equipped with an intelligent early warning function. When abnormal situations are detected, it can quickly issue alarms and notify relevant personnel, such as medical staff and family members. This not only improves the living safety of the elderly but also provides strong support for the management of elderly care communities, promoting the intelligent development of age-friendly living spaces.

4.2. Innovation in investment management mode for age-friendly projects

4.2.1. Optimization of PPP mode financing structure

In the innovation of investment management mode for age-friendly projects, the optimization of the PPP mode financing structure is of vital importance. Government-enterprise cooperative elderly care facility projects need to construct a reasonable risk-sharing model to balance the interests and risks of all parties. Through empirical analysis of the cash flow balance mechanism of a public-built and privately-operated nursing home project in a certain city, an in-depth understanding of the project's financial feasibility and sustainability can be obtained. Reasonable risk sharing can encourage all parties to actively participate in the project and improve the success rate of the project. Meanwhile, optimizing the PPP mode financing structure requires considering the whole-lifecycle costs of the project, including construction costs, operation costs, and potential risk costs. Only in this way can the financing structure be ensured to match the actual needs of the project, providing stable financial support for the construction and operation of age-friendly living spaces [9].

4.2.2. Whole-lifecycle cost control

Establishing an operation and maintenance cost prediction model for age-friendly buildings is crucial for whole-lifecycle cost control. This model needs to comprehensively consider various factors such as building materials, equipment maintenance, and labor costs. Through the analysis of costs over a 15-year cycle, a comprehensive understanding of the cost expenditure of age-friendly buildings at different stages can be obtained. At the same time, this analysis can verify the economic feasibility of green building technologies in age-friendly buildings. Although green building technologies may increase the initial investment, they may have significant advantages in terms of long-term operation and maintenance costs. For example, energy-saving equipment can reduce energy consumption costs, and environmentally friendly materials can lower the frequency of maintenance. Through accurate cost prediction models and cycle cost analysis, a scientific basis can be provided for investment management of age-friendly projects, investment decisions can be optimized, and effective control of whole-lifecycle costs can be achieved [10].

5. Multi-dimensional collaborative implementation guarantee system

5.1. Reengineering of standardized management processes

5.1.1. Cross-phase collaborative work interfaces

In whole-process engineering consulting, cross-phase collaborative work interfaces are of vital importance. Taking elderly care projects as an example, formulating a design management-investment control collaboration matrix is key. In the scheme deepening stage, the responsibilities of all participating parties are clarified. For instance, the design unit needs to optimize the design scheme in combination with the investment budget to ensure the balance between functions and costs; the construction unit should provide accurate project positioning and demand information to avoid investment out of control caused by later changes. In the construction drawing design stage, the design unit must carry out the design in strict accordance with specifications and investment limits. The construction unit can intervene in advance to put forward suggestions on construction difficulty and costs, while the investment management party should monitor cost changes in real time. All parties collaborate to ensure the smooth progress of the project and achieve effective collaboration between design management and investment control.

5.1.2. Dynamic optimization feedback mechanism

A dynamic optimization feedback mechanism is established based on the PDCA cycle. In the Plan phase, management objectives and collaborative strategies across various dimensions are clarified, and standardized processes are formulated. In the Do phase, implementation is carried out strictly in accordance with the processes to ensure the multi-dimensional collaborative advancement of design management, investment management, and other aspects. In the Check phase, actual implementation results are compared with expected objectives, and the causes of deviations are analyzed. In the Act phase, improvement measures are taken for identified problems, and collaborative strategies and standardized processes are adjusted. Through the practice of elderly apartment projects, the effective frequency of process iteration and improvement is continuously verified, and collaborative strategies are constantly optimized. This realizes the dynamic management and continuous improvement of multi-dimensional collaboration, ensuring the efficient implementation of whole-process engineering consulting.

5.2. Construction of a digital collaborative platform

5.2.1. BIM-ERP system integration architecture

The construction of the BIM-ERP system integration architecture for the digital collaborative platform needs to be carried out from multiple aspects. A unified data standard should be established first to ensure that the design information in the BIM model can be accurately connected and interacted with the project management and cost data in the ERP system. For example, standardized definitions should be made for the coding and attributes of building components. Then, data transmission interfaces should be built to realize two-way data circulation. Design change information can be timely transmitted from the BIM side to the ERP system, triggering the update of cost data; at the same time, cost control indicators in the ERP system can also be fed back to the BIM model to provide a basis for design optimization. In addition, a data security management mechanism should be established to ensure the integrity and confidentiality of various data in the collaborative process, prevent data leakage and incorrect modifications, and thus effectively support the real-time linkage update of design changes and cost data.

5.2.2. Big data decision support system

On the basis of building a digital collaborative platform, establishing a big data decision support system is of vital importance. It collects data from all links of the whole-process engineering consulting, including multi-dimensional information such as design management and investment management. Machine learning algorithms are used to build cost prediction models to accurately predict the costs of projects such as elderly care homes. At the same time, an in-depth exploration of historical project data is conducted to analyze its application value in investment decisions. This system can integrate data from different sources, eliminate information silos, and provide comprehensive and accurate data support for decision-makers. Through data analysis and processing, potential risks and opportunities can be identified, investment management strategies can be optimized, and the economic and social benefits of projects can be improved. This realizes an effective guarantee of multi-dimensional collaboration at the decision-making level and promotes the efficient development of the whole-process engineering consulting business.

5.3. Compound talent training mechanism

5.3.1. Reconstruction of an interdisciplinary knowledge system

To meet the needs of whole-process engineering consulting, it is necessary to reconstruct an interdisciplinary knowledge system. The key lies in the modular design of courses covering multiple disciplines such as architecture, engineering economics, and gerontology. The architecture course module should include content such as architectural design principles and construction technology to cultivate design capabilities. The engineering economics module covers engineering cost estimation, investment benefit analysis, etc., to improve economic analysis skills. The gerontology module involves knowledge such as the characteristics of the elderly's needs and age-friendly design to meet the needs of specific projects. At the same time, a continuing education framework for practitioners should be built to update knowledge regularly. Through a combination of online and offline methods, course content such as case studies and special lectures is provided to ensure that practitioners can timely master interdisciplinary cutting-edge knowledge, improve their comprehensive literacy, and better deal with complex problems in whole-process engineering consulting projects.

5.3.2. Construction of school-enterprise joint practice base

The BIM training center, co-founded by a university and a design institute, has achieved remarkable results in cultivating compound talents. The two parties integrate resources: the university provides a theoretical teaching foundation, while the design institute brings practical project experience. In the practice base, students participate in real, whole-process consulting projects, learning from multiple dimensions such as design management and investment management. Through practical operations, students gain an in-depth understanding of the importance of collaboration in various links. Meanwhile, the training center has formulated a sound talent training program covering curriculum setup, practical teaching arrangements, and assessment mechanisms. The curriculum setup is aligned with industry needs, emphasizing the integration of theory and practice. Practical teaching arranges for students to participate in projects at different stages, enhancing their ability to solve practical problems. The assessment mechanism comprehensively evaluates students' mastery of theoretical knowledge and performance in practical operations, ensuring that the cultivated talents are compound ones meeting the needs of the whole-process engineering consulting industry.

6. Conclusion

The whole-process engineering consulting model has significantly improved the comprehensive benefits of public buildings and age-friendly projects, reaching 15–20%. The dynamic collaboration between design management and investment control can reduce the whole-cycle cost by 8–12%. From this perspective, multi-dimensional collaboration, such as design management and investment management, is crucial. At the same time, attention should be focused on the application of intelligent perception technology in spatial age-friendly evaluation and the digital transformation path of project consulting services under the background of new infrastructure. This not only helps to further improve project benefits and optimize cost control, but also adapts to the needs of the times, promotes whole-process engineering consulting to better serve various projects, and realizes more efficient and scientific project management and implementation.

Disclosure statement

The author declares no conflict of interest.

References

[1] Li J, 2021, Research on Core Business of Design Management in EPC Projects from the Perspective of Whole-Process Engineering Consulting, dissertation, Tianjin University of Technology.

[2] Liu M, 2022, Research on Multi-agent Collaboration Mechanism in Whole-Process Engineering Consulting, dissertation, Chongqing Jiaotong University.

[3] Du Y, 2021, Research on Risk Management of Whole-Process Engineering Consulting Project A, dissertation, Shandong University.

[4] Gu F, 2023, Study on Multi-Agent Collaborative Governance Factors in Whole-Process Engineering Consulting for Large Water Conservancy Projects, dissertation, Nanchang University.

[5] Qian C, 2023, Research on Risk Management of Whole-Process Engineering Consulting in University Infrastructure Projects, dissertation, Zhongyuan University of Technology.

[6] Zhang X, Liu X, 2019, Prospects of Engineering Cost Consulting Business under Whole-Process Engineering Consulting. Engineering Cost Management, (6): 52–56.

[7] Qi Z, Wei C, Dong S, 2021, Research on Development of Whole-Process Engineering Consulting from Government-Enterprise Collaboration Perspective. Construction Economy, 42(4): 98–101.

[8] Cao X, 2022, Exploration of Investment Management Mode in Whole-Process Engineering Consulting Projects. Construction Supervision, 2022(1): 30–32.

[9] Ma Y, 2022, Research on Design Management Based on Whole-Process Engineering Consulting. Engineering and Technological Research, 7(8): 182–184.

[10] Li F, 2010, Preliminary Study on Participation of Engineering Cost Consulting Units in Whole-Process Cost Management. Co-Operative Economy & Science, (24): 70–71.

Journal of Architectural Research and Development, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Optimization of Water Supply and Drainage System: Coordinated Development of Pipeline Network Maintenance and Sewage Plant Expansion and Operation

Jianwei Deng*

Shenzhen 518000, China

**Author to whom correspondence should be addressed.*

Abstract: This article focuses on the optimization of water supply and drainage systems, involving theories such as hydraulic models of pipeline systems and multi-objective collaborative optimization. It introduces the system dynamics model of sewage treatment facility expansion. Elaborating on detection technology, construction of an intelligent operation and maintenance system, and factors to be considered for sewage plant expansion, it emphasizes the importance of collaborative development and verifies benefits through the PSR model.

Keywords: Water supply and drainage system; Pipeline network maintenance; Expansion of sewage treatment plant

Online publication: October 10, 2025

1. Introduction

With the acceleration of urbanization, the water supply and drainage system is facing many challenges, and the coordinated development of pipeline maintenance and sewage plant expansion and operation has become the key. The *Several Opinions on Strengthening Urban Infrastructure Construction*, released in 2022, emphasizes the importance of improving the level of urban infrastructure construction. In this context, the optimization of the water supply and drainage system needs to be carried out from multiple aspects. This involves the construction of hydraulic models for pipeline systems, the application of multi-objective collaborative optimization strategies, the establishment of system dynamics models for sewage treatment facility expansion projects, the application of detection technology, the construction of smart pipeline operation and maintenance systems, the matching of sewage plant expansion processes and the improvement of treatment capacity, collaborative optimization, the development of intelligent aeration control systems, the construction of digital twin models, the linkage between pipeline coverage and plant site selection, the composite utilization of land resources, the establishment of joint investment decision-making models, and the construction of cross departmental information sharing platforms, in order to achieve efficient operation and sustainable development of the water supply and drainage system.

2. Theoretical basis for collaborative development of water supply and drainage systems

2.1. Theoretical framework for optimization of water supply and drainage network system

The theoretical framework for optimizing water supply and drainage pipeline systems involves the principles of constructing hydraulic models for pipeline systems and the application mechanism of multi-objective collaborative optimization strategies. The hydraulic model construction of the pipeline system is based on the basic principles of fluid mechanics, considering the continuity equation and energy equation of water flow, combined with the topology structure and pipeline characteristics of the pipeline network, and accurately describing the water flow state inside the pipeline network through mathematical modeling methods [1]. The application of a multi-objective collaborative optimization strategy in pipeline maintenance and sewage plant expansion requires comprehensive consideration of multiple objectives, such as cost, water quality, and water quantity. By establishing an objective function and using optimization algorithms to find the optimal solution, we aim to achieve rational resource allocation and overall system performance improvement. This collaborative optimization mechanism can meet the needs of sewage treatment while reducing maintenance costs and operational risks, and improving the sustainability and stability of the water supply and drainage system.

2.2. System dynamics analysis of sewage treatment plant expansion and operation

Establishing a system dynamics model for the expansion project of sewage treatment facilities is key to understanding its complex operating mechanism. Through this model, the coupling relationship between production capacity matching, environmental capacity, and economic costs can be explored in depth. Capacity matching involves the adaptation of sewage treatment capacity to the amount of sewage generated, which directly affects the effectiveness and efficiency of sewage treatment [2]. The environmental capacity determines the limit of sewage discharge and plays an important guiding role in the treatment scale and technology selection of sewage plants. Economic costs cover multiple aspects such as construction, operation, and maintenance, and are factors that cannot be ignored in the decision-making process. These factors are interrelated and influence each other, and the system dynamics model can simulate their dynamic changes, providing a scientific decision-making basis for the expansion and operation of sewage treatment plants.

3. Research on key technologies for pipeline network maintenance

3.1. Pipeline health diagnosis and early warning technology

CCTV detection technology can penetrate deep into the pipeline network and obtain internal image information through high-definition cameras, accurately identifying structural defects such as cracks and deformations. Hydraulic pressure testing relies on monitoring and analyzing pressure changes in the pipeline network to infer whether there are damage and leakage issues in the pipeline. A leakage warning system based on the Internet of Things installs sensors at key nodes of the pipeline network to collect real-time data, such as pressure and flow, and transmit it to the monitoring center [3]. Using data analysis algorithms to process data, issuing timely warnings when data anomalies occur, achieving real-time monitoring and rapid response to pipeline leakage, and effectively ensuring the normal operation of the pipeline network.

3.2. Construction of an intelligent pipeline network operation and maintenance system

The construction of an intelligent pipeline operation and maintenance system requires the use of advanced technology to improve management efficiency and accuracy. The GIS BIM integrated platform plays an important role in pipeline asset management. Its technical path includes data collection and integration, 3D model construction, and real-time information updates [4]. By integrating spatial data from geographic information systems (GIS) and detailed attribute data from building information models (BIM), it achieves comprehensive visual management of pipeline assets. The development and application of a preventive maintenance decision support system is also crucial. The system can analyze pipeline operation data, historical maintenance records, and real-time monitoring information, predict possible failure points and maintenance needs, provide a scientific basis for the formulation of maintenance plans, thereby improving the initiative and effectiveness of pipeline maintenance, reducing maintenance costs and failure risks.

4. Collaborative optimization of sewage plant expansion project

4.1. Expansion process compatibility design

4.1.1. Load forecasting and processing capacity improvement plan

The expansion of sewage treatment plants requires comprehensive consideration of multiple factors to achieve process matching and improve treatment capacity. Based on the population growth model, predict the trend of changes in sewage production, and combine it with the demand for improving water quality standards to develop reasonable expansion process selection strategies for different stages. For example, with the increase in population and industrial development, the composition and concentration of pollutants in sewage may change, and processes that can effectively treat new pollutants need to be selected. For the improvement of processing capability, it can be achieved by increasing the number of processing units and optimizing the operating parameters of existing units [5]. At the same time, it is necessary to ensure that the expanded process can operate in coordination with the original process, avoiding problems such as poor connection, in order to ensure the stable and efficient operation of the sewage treatment plant.

4.1.2. Network sewage plant linkage regulation and storage mechanism

To achieve optimization of the water supply and drainage system, it is necessary to synergistically optimize the storage capacity of the pipeline network and the treatment process of the sewage plant. On the one hand, analyzing the storage capacity characteristics of the pipeline network, including the influence of different pipe diameters, materials, and laying methods on storage, and determining its storage potential under different working conditions [6]. On the other hand, in combination with the treatment process requirements for the expansion of the sewage treatment plant, the two should be matched with each other. For example, for biological treatment processes, it is necessary to ensure the stability of the water quality and quantity of the sewage transported by the pipeline network, and to avoid the impact of shock loads on microorganisms. When constructing a peak load response plan for the rainy season, the storage capacity of the pipeline network is utilized to temporarily store excess rainwater, and the flow entering the sewage treatment plant is reasonably allocated to avoid overloading. At the same time, by optimizing the operating parameters of the sewage treatment plant, the treatment efficiency is improved to ensure that the effluent quality meets the standards.

4.2. Intelligent operation of expansion projects

4.2.1. Optimization design of an intelligent control system

Develop an intelligent aeration control system based on MBR technology, which can accurately control the aeration process of sewage treatment plants. By monitoring various indicators in sewage in real-time, such as dissolved oxygen content and organic matter concentration, the system can automatically adjust the aeration intensity and time according to preset algorithms. This can ensure effective treatment of pollutants in sewage and avoid energy waste caused by excessive aeration, thereby achieving a balance and optimization of energy consumption and treatment efficiency. The system can also be integrated with other intelligent control systems of the sewage treatment plant to achieve information sharing and collaborative work, further improving the overall operational efficiency and management level of the sewage treatment plant [7].

4.2.2. Application practice of digital twin technology

Building a digital twin model for sewage treatment plants is the key to achieving collaborative optimization and intelligent operation of sewage plant expansion projects. By accurately collecting physical data of sewage treatment plants, including equipment operating parameters and water quality and quantity changes, advanced modeling techniques are used to create virtual digital twin models. This model can reflect the actual operating status of sewage treatment plants in real time and simulate and analyze expansion projects. By simulating different operating conditions and expansion plans, the improvement effect of expansion projects on system processing efficiency can be accurately evaluated. For example, predicting the extent of improvement in sewage treatment capacity after expansion and its impact on water quality improvement [8]. This not only provides a scientific basis for engineering decision-making but also enables refined management and optimized control of sewage treatment plants through the interaction between digital twin models and actual systems during operation.

5. Collaborative development mechanism and empirical research

5.1. Space collaborative planning mechanism

5.1.1. Analysis of the linkage between pipeline coverage and plant site selection

In the optimization of water supply and drainage systems, the linkage between pipeline coverage and plant site selection is crucial. Using geographic spatial analysis techniques, taking into account multiple factors such as terrain, population distribution, and water flow direction [9], optimize the topology structure of the pipeline network and the site selection plan for sewage treatment plants. Firstly, analyze the weak areas covered by the existing pipeline network and potential locations for sewage treatment plant construction to improve sewage collection efficiency. By simulating the water flow path and pollutant diffusion situation, determine the appropriate direction of the pipeline network and the location of the sewage treatment plant to ensure that the sewage can be effectively transported to the treatment plant. At the same time, considering future urban development plans and population growth trends, space is reserved for pipeline network expansion and sewage plant expansion to achieve sustainable and coordinated development of the water supply and drainage system.

5.1.2. Comprehensive utilization mode of land resources

The composite utilization mode of land resources under the spatial collaborative planning mechanism is crucial in optimizing the water supply and drainage system. Reasonable spatial coordination development is required between underground pipe galleries and above-ground facilities. For example, in combination with the expansion needs of sewage treatment plants, when planning land use, the construction of underground pipe galleries can be integrated with the layout of sewage pipelines to improve land use efficiency while ensuring the efficient operation of the water supply and drainage system [10]. At the same time, the expansion of above-ground facilities such as sewage treatment plants should be coordinated with the surrounding land use planning to avoid adverse effects on the surrounding environment and other land uses. By reasonably planning the spatial layout of underground pipe galleries and above-ground facilities, the composite utilization of land resources can be achieved, promoting the optimization of water supply and drainage systems and the coordinated development of the entire urban infrastructure.

5.2. Management collaborative innovation mechanism

5.2.1. Whole-lifecycle cost control system

Establishing a joint investment decision-making model that covers pipeline maintenance and sewage plant expansion is key to achieving whole-lifecycle cost control. This model needs to comprehensively consider the cost factors of the pipeline network and sewage treatment plant at different stages, including construction costs, operating costs, and maintenance costs. During the construction phase, it is necessary to weigh the impact of pipeline materials, pipe diameters, sewage treatment processes, and scale on costs. During the operation process, analyze the impact of changes in sewage treatment capacity and water quality on costs. At the same time, consider factors related to maintenance costs, such as maintenance frequency and the difficulty of repairs. By integrating these factors, a dynamic joint investment decision-making model is constructed to achieve the rational allocation of resources, minimize the whole-lifecycle cost, and promote the coordinated development of pipeline maintenance and sewage plant expansion and operation in the water supply and drainage system.

5.2.2. Construction of a cross-departmental information sharing platform

Building a cross-departmental information-sharing platform is crucial in the water supply and drainage system. Design a data exchange mechanism for water supply and drainage facility management based on blockchain technology, which can achieve secure and efficient data sharing. The distributed ledger feature of blockchain ensures the immutability and traceability of data, making the maintenance, operation, and other aspects of water supply and drainage facilities data authentic and reliable. Different departments can obtain the required information in real time through this platform, such as the pipeline maintenance department being able to timely understand the operation data of the sewage plant in order to arrange maintenance plans reasonably; wastewater treatment plants can also obtain real-time information on the pipeline network and optimize expansion and operation strategies. This information-sharing mechanism breaks down information barriers between departments, improves collaborative work efficiency, and promotes the overall optimization and sustainable development of the water supply and drainage system.

5.3. Empirical study: A case study of the Guangdong Hong Kong Macao Greater Bay Area

5.3.1. Analysis of regional load characteristics

The industrial agglomeration area in the Greater Bay Area has a unique industrial structure, and its special water quality characteristics have multiple impacts on the coordinated development of the water supply and drainage system. On the one hand, some industries, such as electronic information and biomedicine, may discharge wastewater containing special chemicals, which puts higher demands on the treatment process of sewage plants. These substances may affect microbial activity, reduce sewage treatment efficiency, and increase treatment costs. On the other hand, the variation in water quantity of special water quality may be related to the industrial production cycle, leading to unstable inflow load of sewage treatment plants. For example, some industries may discharge large amounts of wastewater during peak production seasons, exceeding the treatment capacity of sewage plants, while during off-seasons, the amount of wastewater discharged sharply decreases, affecting the stable operation of sewage plants. This requires full consideration of these special water quality characteristics in the coordinated development process of pipeline maintenance and sewage plant expansion and operation, in order to achieve efficient operation of the water supply and drainage system.

5.3.2. Evaluation of collaborative optimization effectiveness

Validate the benefits of collaborative development through the PSR model. At the Pressure level, evaluate the pressure of population growth, urbanization process, and other factors on the water supply and drainage system, as well as how inadequate maintenance of the pipeline network and insufficient expansion of sewage treatment plants exacerbate these pressures. At the State level, analyze the operational status of the existing water supply and drainage system, including the degree of pipe network aging, sewage treatment capacity, etc., to determine the starting point for collaborative optimization. At the Response level, consider the implementation of pipeline maintenance measures and sewage plant expansion and operation strategies, as well as their mutual coordination effects. By integrating the three levels of PSR, constructing an indicator system, using appropriate data analysis methods, and quantifying the benefits of collaborative development, such as the improvement of sewage discharge rate and water resource recycling rate, it provides a basis for the continuous optimization of the water supply and drainage system.

6. Conclusion

The optimization of water supply and drainage systems is crucial for the sustainable development of cities. The coordinated development of pipeline maintenance and sewage plant expansion and operation is the key to achieving this goal. Through collaborative optimization, the efficiency and reliability of the water supply and drainage system can be improved, reducing energy consumption and environmental pollution. The implementation path includes strengthening pipeline monitoring and maintenance, optimizing sewage treatment processes, and improving water resource recycling and utilization. The value of innovation lies in improving the adaptability and resilience of the system, and promoting the sustainable development of cities. In the future, digital twins and low-carbon treatment technologies will provide new opportunities and challenges for optimizing water supply and drainage systems. Facing the new urbanization, it is necessary to further strengthen the integration and optimization of the water supply and drainage system, improve the intelligence level and management efficiency of the system, and achieve sustainable utilization of water resources and sustainable development of cities.

Disclosure statement

The author declares no conflict of interest.

References

[1] Abbasi N, Bahramloo R, Movahedan M, 2015, Strategic Planning for Remediation and Optimization of Irrigation and Drainage Networks: A Case Study for Iran. Agriculture and Agricultural Science Procedia, 4: 211–221.

[2] Zhao W, Beach TH, Rezgui Y, 2015, Optimization of Potable Water Distribution and Wastewater Collection Networks: A Systematic Review and Future Research Directions. IEEE Transactions on Systems, Man, and Cybernetics: Systems, 46(5): 659–681.

[3] Ngamalieu-Nengoue UA, Martinez-Solano FJ, Iglesias-Rey PL, et al., 2019, Multi-Objective Optimization for Urban Drainage or Sewer Networks Rehabilitation Through Pipes Substitution and Storage Tanks Installation. Water, 11(5): 935.

[4] Wang J, Liu G, Wang J, et al., 2021, Current Status, Existing Problems, and Coping Strategy of Urban Drainage Pipeline Network in China. Environmental Science and Pollution Research, 28(32): 43035–43049.

[5] Dijk VD, Hendrix ME, 2016, Pipe Replacement in a Water Supply Network: Coordinated Versus Uncoordinated Replacement and Budget Effects. Informatica, 27(2): 387–403.

[6] Tian J, He G, 2020, Optimization Design Method for Urban Sewage Collection Pipe Networks. Water Science and Technology, 81(9): 1828–1839.

[7] Ramos-Salgado C, Munuzuri J, Aparicio-Ruiz P, et al., 2021, A Decision Support System to Design Water Supply and Sewer Pipes Replacement Intervention Programs. Reliability Engineering & System Safety, 216: 107967.

[8] Ramos-Salgado C, Munuzuri J, Aparicio-Ruiz P, et al., 2022, A Comprehensive Framework to Efficiently Plan Short and Long-Term Investments in Water Supply and Sewer Network. Reliability Engineering & System Safety, 219: 108248.

[9] Joseph K, Sharma AK, Van Staden R, 2022, Development of an Intelligent Urban Water Network System. Water, 14(9): 1320.

[10] Teichmann M, Kuta D, Endel S, et al., 2020, Modeling and Optimization of the Drinking Water Supply Network—A System Case Study from the Czech Republic. Sustainability, 12(23): 9984.

Journal of Architectural Research and Development, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Research on the Quality Management Strategy and Practice of Building Curtain Wall Construction

Lichong Duan*

Shenzhen Yougaoya Building Decoration Co., Ltd., Shenzhen 518000, Guangdong, China

**Author to whom correspondence should be addressed.*

Abstract: Quality management in building curtain wall construction covers both the essence and scope, including material control and process control. It is crucial for safety, longevity, and energy efficiency. Although quality management models are diverse, they have their limitations. The paper also discusses key points such as quality issues, material and process compatibility, and node construction, along with various techniques and management methods to improve quality. It also highlights areas for further research and future directions.

Keywords: Building curtain wall; Construction quality; Quality management

Online publication: October 10, 2025

1. Introduction

As the outer envelope of a building, the construction quality management of building curtain walls is of vital importance. In recent years, with the continuous improvement of relevant policies in the construction industry, such as the "Quality Acceptance Standard for Building Curtain Wall Engineering" issued in 2019, stricter requirements have been put forward for the construction quality of curtain walls. The connotation of curtain wall construction quality management is rich and varied. It not only covers the control of material quality, management of various construction stages, and oversight of participating entities, but also involves the regulation and supervision of new technology applications. The quality objectives encompass multiple aspects, including safety, functionality, and aesthetics. From the perspectives of building safety, service life, and energy conservation and environmental protection, a scientific quality management system is indispensable. At the same time, although there are diverse quality management models currently in use, they have their shortcomings. There are also many quality issues in construction. These problems not only affect the overall performance of the building but may also bring safety hazards and increased maintenance costs. All these factors highlight the necessity of in-depth research and optimization of the construction quality management of building curtain walls.

2. Overview of construction quality management of building curtain wall

2.1. The core concept of curtain wall construction quality management

The quality management of building curtain wall construction is a systematic task to ensure that the quality of curtain wall engineering meets the expected standards. It includes strict control of the quality of curtain wall materials, which directly affects the performance and safety of the curtain wall. For example, the strength of aluminum alloy profiles, the optical properties of glass, and the weather resistance of sealants must all comply with relevant standards [1]. Its scope extends to every link of the construction process and all parties involved. The quality objectives clarify the standards that the curtain wall should meet in terms of safety, functionality, and aesthetics. For instance, the wind pressure resistance of the curtain wall must meet the local climatic conditions. Process control covers every stage of construction, from the installation of embedded parts to the installation of panels, with strict quality monitoring measures for each step. The acceptance criteria serve as the basis for inspecting the final engineering quality, including the detection standards for various indicators such as the plumbness, flatness, and sealing performance of the curtain wall. Research has shown that different project stakeholders have varying perspectives on the quality issues of curtain wall construction, which further highlights the importance of systematic quality management.

2.2. The importance of a quality management system

The quality management system for building curtain wall construction is of vital importance. From the perspective of building safety, the curtain wall, as the outer envelope of a building, may pose safety hazards such as detachment under adverse weather conditions or external forces if its quality is not up to standard, endangering human lives and property. Research has shown that selecting the appropriate curtain wall system is a key factor in ensuring building safety and performance, and a scientific quality management system is the foundation for achieving this goal [2]. In terms of service life, a scientific quality management system can ensure that materials and construction techniques meet the standards, thereby reducing premature damage to the curtain wall caused by quality issues and extending its lifespan. Regarding energy conservation and environmental protection, good quality management helps in selecting appropriate energy-saving materials and rational design details, which can enhance the curtain wall's thermal insulation, heat insulation, and daylighting performance, reduce the energy consumption of buildings, and achieve the goals of energy saving and environmental protection. Moreover, with the increasing emphasis on sustainable development in the construction industry, the quality management of curtain wall construction also needs to consider the efficiency of resource utilization and waste management during the construction process to minimize environmental impact.

3. Analysis of quality management status of curtain wall construction

3.1. Current quality management model

The compatibility of material properties and construction techniques is of vital importance in curtain wall construction. Research has shown that automated evaluation techniques can better optimize curtain wall design, thereby improving the match between material properties and construction techniques to ensure construction quality [3]. The thermal performance of materials needs to be matched with construction techniques to ensure that the curtain wall meets the required insulation and heat insulation effects. For example, different types of insulation materials require specific installation techniques during construction to fully realize their performance. At the same time, the structural strength of materials must also be compatible with construction techniques. Suitable construction techniques can ensure that materials are not damaged during installation, thereby maintaining their structural strength. For instance, the installation technique for glass in glass curtain walls should avoid improper operations that can cause cracks in the glass, affecting its structural safety. Only when material properties and construction techniques are highly compatible can the construction quality of curtain walls be effectively guaranteed.

3.2. Typical quality problems and causes

The construction of building curtain walls faces many quality issues. Water leakage is one of the common problems, caused by the aging of sealants and improper treatment of joints. Over time, sealants degrade due to environmental factors, leading to water infiltration. If the joints are not properly sealed during construction, this can also cause leakage. Deformation is another issue that cannot be ignored, which may result from an improper structural design that cannot withstand external forces. In some cases, the insufficient design strength of the curtain wall frame leads to deformation under wind loads and other external forces. Material degradation is also an important factor causing quality problems. For example, glass breakage may be due to uneven internal stress or external impact, while the corrosion of metal materials can affect their structural strength and stability, thereby affecting the overall quality of the curtain wall [2]. The occurrence of these problems not only affects the normal use of the building but may also bring safety hazards. Therefore, it is necessary to use scientific quality management methods and multi-criteria decision-making models to optimize the selection and construction management of curtain wall systems to reduce the occurrence of quality problems.

4. System of influencing factors of curtain wall construction quality

4.1. Technical influencing factors

4.1.1. Material performance and process adaptability

The compatibility of material properties and construction techniques is of vital importance in curtain wall construction. Studies have shown that automated evaluation techniques can better optimize curtain wall design, thereby improving the match between material properties and construction techniques to ensure construction quality. The thermal performance of materials needs to be matched with construction techniques to ensure that the curtain wall meets the required insulation and heat insulation effects. For example, different types of insulation materials require specific installation techniques during construction to fully realize their performance. At the same time, the structural strength of materials must also be compatible with construction techniques. Suitable construction techniques can ensure that materials are not damaged during installation, thereby maintaining their structural strength. For instance, the installation technique for glass in glass curtain walls should avoid improper operations that can cause cracks in the glass, affecting its structural safety. Moreover, modern technology has also provided new safeguards for curtain wall construction quality. For example, monitoring and analysis methods based on fiber-optic sensing technology have been used for real-time monitoring of curtain wall deformation, which can detect and address potential deformation problems in a timely manner, further enhancing the safety and reliability of curtain walls [4]. Only when material properties and construction techniques are highly compatible and combined with advanced technological means can the construction quality of curtain walls be effectively guaranteed.

4.1.2. Node structure reliability

The reliability of node construction in curtain wall construction is of vital importance. The design of connectors directly affects the stability of the curtain wall structure. The material selection and size specifications must comply with mechanical principles and actual engineering needs. Unreasonable design may lead to uneven force distribution and safety hazards. Sealing treatment affects the waterproofing and airtightness of the curtain wall, and the quality of the sealing material and the rationality of the sealing process are key factors. High-quality sealing materials can effectively prevent the penetration of rainwater and air, while a rational sealing process ensures the durability of the sealing effect. The construction details at the nodes, such as the connection methods and angles of different components, need to be precisely designed and constructed. Any deviation in these details may affect the performance and quality of the entire curtain wall system. Moreover, with the development of building technology, the design, development, and testing of new curtain wall systems, such as building-integrated photovoltaic/thermal (BIPV/T) systems, are continuously advancing. The node construction of these systems needs to consider both electrical and structural performance requirements, further highlighting the importance of node design [5].

4.2. Management influencing factors

4.2.1. Effectiveness of process supervision

The management blind spots in the connection of construction processes and the acceptance of concealed works have a significant impact on the quality of curtain wall construction. Research has shown that the temperature distribution of glass curtain walls in super high-rise buildings poses higher requirements for the quality control of construction processes and concealed works [6]. In terms of the connection of construction processes, a lack of effective communication and coordination between processes can lead to construction delays and poor connections, affecting the overall quality. For example, if the previous process is not completed according to the standard and the subsequent process is forced to proceed, it may cause cumulative errors that endanger the structural safety of the curtain wall. The acceptance of concealed works, due to its own characteristics, is easily overlooked. For example, if problems such as inaccurate installation positions of embedded parts and insecure connections are not detected during acceptance, they cannot be remedied in subsequent construction, directly affecting the stability and durability of the curtain wall. Therefore, strengthening the supervision of these management blind spots is the key to improving the quality of curtain wall construction.

4.2.2. Professional competence

The skill level of construction workers and the quality awareness of management personnel have a significant impact on the quality of curtain wall construction. The professional skills of construction workers cover many aspects, such as their understanding of curtain wall material properties, including the characteristics and applicability of different materials in various environments. For example, large-scale glass curtain walls in high-rise buildings need to have good wind resistance performance. Construction workers must be familiar with the strength and stability of glass materials under wind loads to ensure the safety of the curtain wall [7]. Their installation skills are also crucial. Accurate measurement, cutting, and installation techniques directly affect the overall quality of the curtain wall. At the same time, the familiarity of construction workers with construction standards and regulations determines whether the construction process is compliant. The quality awareness of management personnel affects the working attitude and direction of the entire construction team. They need to have a keen ability to control quality, being able to promptly identify and correct quality issues during construction, and to reasonably arrange construction progress and resources to ensure that the construction process meets quality requirements, thereby ensuring the quality of curtain wall construction. Moreover, with the continuous development of building technology, construction workers and management personnel also need to continuously learn and update their knowledge to meet the challenges brought by new materials, technologies, and construction techniques. Only by improving the professional skills of construction workers and the quality awareness of management personnel can the overall quality of curtain wall construction be effectively enhanced, ensuring the safety and durability of buildings.

5. Quality management optimization strategy and practice path

5.1. Technical control strategy

5.1.1. Intelligent material detection technology

The construction of an automated detection system for curtain wall materials based on spectral analysis and machine vision is key to intelligent material inspection technology. For example, research on a novel glass curtain wall system has shown that its unique thermal characteristics require materials to meet higher performance standards. Spectral analysis technology can accurately identify the chemical composition and physical properties of curtain wall materials to ensure they meet these requirements [8]. Machine vision technology can conduct high-precision inspections of material appearance, such as surface defects and dimensional accuracy. By combining these two technologies, a comprehensive and automated inspection of curtain wall materials can be achieved. This system not only improves detection efficiency and reduces human error but also promptly identifies substandard materials, preventing them from entering the construction phase, thereby effectively ensuring the quality of curtain wall construction.

5.1.2. Innovation of construction process standardization

Unitized curtain wall modular installation can improve construction efficiency and quality. Research has shown that for a novel frame-integrated curtain wall, the selection and characterization of materials are key factors in ensuring its performance [9]. By breaking down the curtain wall into modules and prefabricating them in the factory, the amount of on-site work can be reduced, while the precision and stability of quality can be improved. Meanwhile, three-dimensional scanning-assisted positioning technology provides precise spatial data for construction. During the installation process, three-dimensional scanning devices are used to obtain the actual position information of the main building structure and the installed curtain wall, which is compared and analyzed with the design model to adjust deviations in a timely manner and ensure the accuracy of the curtain wall installation position. These process improvement solutions help to enhance the standardization level of curtain wall construction, ensure construction quality, and reduce quality problems caused by non-standard processes.

5.2. Management mechanism optimization

5.2.1. PDCA cycle quality control model

The PDCA cycle quality control model covers four stages: Plan, Do, Check, and Act. In the Plan stage, it is necessary to formulate detailed quality objectives, standards, and procedures based on the requirements of building curtain wall construction, and clarify the quality control points in each link. During the Do stage, construction operations are strictly carried out in accordance with the plan to ensure that all processes meet the standards, including material selection and installation techniques. In the Check stage, a comprehensive inspection of the construction process and results is conducted, employing various detection methods such as visual inspection and performance testing to identify quality issues in a timely manner. In the Act stage, the causes of the identified problems are analyzed, improvement measures are developed and fed back to the Plan stage, and subsequent construction is adjusted and optimized. This forms a continuous cycle of quality management, constantly enhancing the quality of building curtain wall construction.

5.2.2. Multi-entity collaborative management platform

Establishing a digital collaboration mechanism that links owners, designers, constructors, and supervisors is key to enhancing the quality management of building curtain wall construction. By creating a unified digital platform, all parties can share construction information in real time, including design drawings, construction progress, and quality inspection reports. Owners can keep abreast of project developments and voice their opinions and demands; designers can optimize and adjust designs based on actual construction conditions; constructors can strictly follow design requirements and standards, and promptly report issues encountered during construction; and supervisors can effectively oversee the construction process to ensure it meets quality standards. Moreover, the platform should also have data analysis capabilities to analyze various types of data during construction, providing a scientific basis for quality management decisions, thereby achieving comprehensive and dynamic management of the quality of building curtain wall construction.

5.3. Application of information technology

5.3.1. In-depth application of BIM technology

During the construction of building curtain walls, BIM technology can be deeply applied in many aspects. It is crucial to develop a collision detection function module for curtain wall construction. By creating precise 3D models, potential collision issues between the curtain wall structure, the main building structure, and various curtain wall components can be identified in advance. This allows for timely adjustments to the design scheme, avoiding rework and delays during construction. Meanwhile, a dedicated schedule simulation function module can visually simulate the construction progress of the curtain wall. Based on the construction plan, it sets the time nodes and logical relationships for each process, displaying the construction process in a virtual environment and analyzing the rationality of the schedule and potential risks. The construction team can optimize resource allocation and construction sequence accordingly, ensuring that the curtain wall construction progresses as planned and improving construction efficiency and quality.

5.3.2. Real-time monitoring system using Internet of Things

In the construction of building curtain walls, the deployment of an IoT-based real-time monitoring system can optimize quality management. Utilizing a network of stress and strain sensors, dynamic monitoring of the construction process can be achieved. These sensors can accurately detect the stress and strain conditions of the curtain wall structure at various stages of construction and transmit the data in real-time to the monitoring system. The system analyzes and processes the data, and if any anomalies are detected, it can issue timely warnings to alert construction personnel to potential quality issues. This enables the construction team to promptly take measures to adjust construction techniques or reinforce local structures, preventing the accumulation of quality risks. Moreover, by analyzing a large amount of monitoring data, quality patterns during the construction process can be summarized, providing references for subsequent construction and further enhancing the stability and reliability of construction quality.

6. Conclusion

The quality management of building curtain wall construction is of vital importance. In terms of key technical approaches, it covers every link from material selection to construction techniques, ensuring the stability, airtightness, and aesthetics of the curtain wall. Innovations in management include the introduction of advanced information management tools and enhanced collaboration among all parties involved. However, there are some shortcomings in the current research. For instance, in terms of adaptability to complex climates, the long-term impact of different climatic conditions on curtain wall performance has not been fully considered. In terms of lifecycle cost control, there is a lack of effective cost forecasting and optimization strategies. Looking to the future, artificial intelligence algorithms hold broad application prospects in the field of quality prediction. By learning from and analyzing a large amount of construction data, potential quality issues can be predicted in advance, providing strong support for quality control during the construction process and thereby further enhancing the quality of building curtain wall construction.

Disclosure statement

The author declares no conflict of interest.

References

[1] Eom J, Kang Y, 2022, Curtain Wall Construction: Issues and Different Perspectives among Project Stakeholders. Journal of Management in Engineering, 38(5): 04022054.

[2] Hamida H, Alshibani A, 2021, A Multi-Criteria Decision-Making Model for Selecting Curtain Wall Systems in Office Buildings. Journal of Engineering, Design and Technology, 19(4): 904–931.

[3] Almerino PM, 2022, Advancing an Automated Evaluation in the Design of a Curtain Wall. Journal of Agriculture and Technology Management, 25(1): 79–87.

[4] Xu D, Wang Y, Xie J, 2022, Monitoring and Analysis of Building Curtain Wall Deformation Based on Optical Fiber Sensing Technology. Iranian Journal of Science and Technology, Transactions of Civil Engineering, 46(4): 3081–3091.

[5] Rounis ED, Athienitis AK, Stathopoulos T, 2021, BIPV/T Curtain Wall Systems: Design, Development and Testing. Journal of Building Engineering, 42: 103019.

[6] Li S, Chen S, 2022, Field Monitoring and Prediction on Temperature Distribution of Glass Curtain Walls of a Super High-Rise Building. Engineering Structures, 250: 113405.

[7] Chen B, Jiang L, Zhang L, et al., 2023, Wind Resistance Performance of Large-Scale Glass Curtain Walls Supported by a High-Rise Building. Buildings, 13(3): 636.

[8] Feng C, Chen X, Wang R, et al., 2022, Study on Thermal Characteristics of a Novel Glass Curtain Wall System. Journal of Thermal Science, 31(6): 1959–1969.

[9] Gargallo M, Cordero B, Garcia-Santos A, 2021, Material Selection and Characterization for a Novel Frame-Integrated Curtain Wall. Materials, 14(8): 1896.

Journal of Architectural Research and Development, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Technical Management of Concrete Mixing Plants: Exploring Pathways to Enhance Quality and Efficiency

Menglong Guan*

Shenzhen 518103, Guangdong, China

**Author to whom correspondence should be addressed.*

Abstract: This paper focuses on the technical management of concrete mixing plants. It introduces the whole-process engineering consulting model and elaborates on multifaceted aspects of technical management, including a matrix-based management framework, standardized design management pathways, cost early-warning systems, approval strategies, regulatory databases, etc. This paper also emphasizes the importance of innovations in collaborative management mechanisms for improving quality and efficiency.

Keywords: Concrete mixing plant; Technical management; Collaborative management

Online publication: October 10, 2025

1. Introduction

Technical management of concrete mixing plants is a complex and critical field involving multifaceted elements. With China's increasing emphasis on the management of engineering construction, relevant policies have been successively introduced. For instance, the 2017 release of the *Guiding Opinions on Promoting the Transformation, Upgrading, and Innovative Development of the Engineering Supervision Industry* highlighted the importance of innovating engineering management models. As an innovative approach, the whole-process engineering consulting model, particularly its "1+N" framework, offers new perspectives for the technical management of concrete mixing plants. Against this backdrop, technical management of mixing plants needs to be constructed from multiple dimensions, including management frameworks, decision weight allocation, standardized design management, cost early-warning systems, and optimization of approval strategies. These efforts aim to enhance quality and efficiency while achieving sustainable development.

2. Construction of the project management theoretical framework

2.1. Analysis of the whole-process engineering consulting model

The whole-process engineering consulting model is an innovative engineering management approach centered on the "1+N" framework. "1" refers to project management, while "N" encompasses specialized services such as engineering supervision, cost consulting, and tendering agency. This model emphasizes the overarching role of project management in integrating diverse professional services to achieve information sharing, collaborative operations, and enhanced efficiency and quality in engineering management. Regarding the collaborative mechanism between project management and engineering supervision, project management establishes overall objectives and plans, whereas engineering supervision focuses on monitoring construction processes and quality control. Their synergy ensures smooth project execution. Compared to traditional management models, the whole-process consulting approach demonstrates significant efficiency advantages. It eliminates information silos, reduces coordination costs, improves decision-making efficiency, and delivers more comprehensive and professional services for engineering construction [1].

2.2. Construction of a technical management model for mixing plants

The construction of a technical management model for a concrete mixing plant needs to establish a system from multiple dimensions. The matrix management framework should comprehensively cover six core elements, such as design, investment, and approval, forming an interconnected management network. The design link should be based on the actual production needs of the mixing plant, combined with future plans for capacity expansion and technological upgrading, to ensure that the design of equipment layout, process flow, etc., not only meets current production standards but also has room for expansion [2]. Investment management needs to balance cost control and benefit output, accurately calculate the input-output ratio in links such as equipment procurement and site construction, to avoid capital waste or insufficient investment affecting production efficiency. The approval process must strictly align with industry norms and policy requirements, and proceed in accordance with legal procedures from project approval to environmental assessment, ensuring the legality and compliance of the mixing plant's operation.

The decision weight allocation model needs to assign differential values based on the degree of influence of each element on technical management. The design link has a prominent weight proportion because it directly determines the basic production capacity, while the investment and approval elements follow closely as they are related to project feasibility. Quantifying the priority of each element in management decisions through weights provides a clear basis for judgments in complex decision-making scenarios, reduces subjective deviations, promotes the transformation of technical management of the mixing plant from experience-driven to data-supported, and comprehensively improves the overall management efficiency.

3. Strategies for building a technical management system

3.1. Standardizing the design management pathway

In the technical management of concrete mixing plants, standardizing the design management pathway is a core element for enhancing production efficiency. Utilizing BIM technology for three-dimensional simulation and optimization of mix proportions enables the transformation of parameters for materials like cement, sand, aggregates, and admixtures into visual models. This intuitively presents key indicators such as concrete strength and workability under different mix ratios, providing a scientific basis for precise batching during production [3].

Establishing a material selection database requires systematic integration of the physical and chemical properties, applicable working conditions, and quality standards of various raw materials. For example, information such as setting times for different grades of cement and aggregate gradation ranges should be included to facilitate rapid matching of optimal material combinations based on project requirements during production, thereby reducing selection errors.

Formulating equipment configuration standards should clearly define model parameters and quantity ratios for mixer hosts, batching machines, conveying equipment, etc., ensuring interface compatibility and capacity matching between devices to avoid production interruptions caused by equipment incoordination. Through these standardization measures, a comprehensive process specification—from material selection to equipment coordination—is formed, driving the transformation of concrete mixing plant technical management toward refinement and efficiency.

3.2. Dynamic control methods for investment management

Establishing a full-cycle cost early-warning system requires multi-dimensional integration of elements. Developing an accurate cost accounting model must cover all process stages, including raw material procurement, equipment maintenance, and labor costs [4]. By detailing the cost composition of each stage, a dynamically updated cost database is formed. Real-time monitoring of cost data and comparison against budget thresholds enables rapid identification of abnormal fluctuations—such as sudden spikes in raw material prices or excessive maintenance expenses—providing precise targets for cost control.

To address raw material price volatility, specialized compensation schemes should be formulated. Sign price adjustment clauses with suppliers to define market fluctuation thresholds, automatically triggering procurement price adjustments when preset ranges are exceeded. A synchronized price monitoring mechanism tracks market conditions in real time, supporting price negotiations and procurement strategy adjustments. The dynamic budget adjustment mechanism must flexibly respond by combining cost early-warning information with production realities. If cost overrun risks emerge or production plans change, timely adaptive adjustments should be made to budgets across all stages. This maintains both production continuity and the economic efficiency of investment management, shifting cost control in mixing plants from reactive responses to proactive prevention.

4. Practice paths of whole-process management

4.1. Innovation mechanism for approval management

4.1.1. Optimization of the environmental protection approval process

The application for production licenses adopts a parallel approval strategy to break the inefficient barriers of traditional serial approval. By integrating the approval processes of environmental protection, industry and commerce, safety supervision, and other relevant departments, the originally sequential links such as material review, on-site inspection, and qualification verification are carried out simultaneously, which greatly shortens the approval cycle, enables enterprises to meet the conditions for compliant operation faster, and directly improves the efficiency of operation startup [5].

The construction of a dynamic monitoring system for environmental assessment indicators needs to cover key parameters such as dust emission concentration, noise decibel value, and wastewater treatment effect. The system captures data fluctuations in real time: when dust emissions are close to the limit, it automatically triggers the spray dust suppression equipment to enhance operation; when noise exceeds the standard, it timely adjusts the production time or activates sound insulation devices. Dynamically optimizing production processes and environmental protection measures based on monitoring data can not only ensure that production activities continuously meet environmental protection standards, help successfully pass various approvals, but also promote transformation into green production, and enhance social credibility and market competitiveness.

4.1.2. Legal risk pre-control system

Establishing a policy and regulation database forms the foundation of the legal risk pre-control system for concrete mixing plants. This database must systematically integrate policy provisions and updates across environmental protection, land use, safety production, and other domains. Information such as environmental emission limits and land approval procedures should be categorized by applicable scenarios and precisely matched to corresponding management stages, providing comprehensive and accurate legal references for corporate decision-making [6].

Designing a dynamic assessment model for land use compliance requires real-time tracking of changes in critical indicators, including land use nature, floor area ratio, and setback distances. By comparing current regulatory requirements with actual land conditions, the model automatically identifies potential conflicts—such as overdue temporary land use or encroachment on planning red lines—enabling enterprises to promptly implement corrective measures and eliminate risks.

This system design ensures continuous alignment with legal norms throughout operations while accelerating responsiveness to approval requirements during permitting processes, thereby shortening procedural timelines. By preemptively avoiding legal violations and enhancing approval efficiency, it establishes a solid legal foundation for the stable production and long-term development of concrete mixing plants.

4.2. On-site management technology innovation

4.2.1. Standardized management of production processes

Standardized management of production processes in concrete mixing plants is crucial for ensuring production quality and efficiency. To guarantee the precision of concrete mix proportions, procedures for real-time moisture content monitoring of aggregates must be established. By continuously tracking aggregate moisture levels, the system dynamically adjusts water dosage and aggregate quantities, effectively preventing mix deviations caused by moisture fluctuations and ensuring consistent concrete quality. This measure significantly enhances concrete strength and workability, providing reliable material support for engineering projects.

Simultaneously, developing an equipment operation status early-warning system is a key initiative for optimizing on-site management. Through real-time monitoring of core equipment such as mixer hosts and batching machines, the system comprehensively tracks operational conditions. Upon detecting abnormalities—such as motor failures or conveying system deviations—the warning system immediately triggers alerts, prompting rapid maintenance interventions by personnel. This proactive warning mechanism effectively prevents production interruptions caused by equipment failures, reduces downtime losses, and ensures process continuity. With real-time monitoring and rapid response capabilities, the system lowers maintenance costs while improving production efficiency and product quality.

The integration of standardized management and an intelligent early-warning system provides an efficient solution for on-site management in concrete mixing plants. Aggregate moisture monitoring ensures mix proportion accuracy, while the equipment warning system safeguards production stability. These elements complement each other, driving production processes toward automation and intelligence, thereby establishing a solid foundation for high-quality and high-efficiency operations in mixing plants.

4.2.2. Intelligent upgrade of quality monitoring

In the technical management of concrete mixing plants, the intelligent upgrade of quality monitoring is a core element for enhancing quality and efficiency. IoT sensor networks are deployed to build concrete strength prediction models, which collect real-time critical production data—such as cement dosage and aggregate ratios—providing precise foundations for quality control [7]. These models dynamically analyze concrete strength trends, promptly identifying potential quality risks to ensure products meet design specifications. Simultaneously, the implementation of online slump testing systems further strengthens quality monitoring capabilities. By tracking concrete slump in real time, the system rapidly detects abnormal fluctuations, guaranteeing workability compliance and preventing construction issues caused by inadequate or excessive fluidity.

These intelligent technologies significantly drive innovation in on-site management techniques, transforming quality monitoring from traditional manual inspections to automated, intelligent processes [8]. Throughout the whole-process management cycle—from raw material inspection to concrete production, transportation, and pouring—every phase achieves precise control via IoT technologies and online testing systems. This end-to-end intelligent management effectively reduces quality incident rates, boosts production efficiency, and provides technical assurance for high-quality operations of concrete mixing plants. Concurrently, it accelerates the industry's shift toward intelligent and refined development, delivering more reliable material support for engineering projects.

5. Innovations in collaborative management mechanisms

5.1. Contract management risk prevention

5.1.1. Dynamic delineation of responsibility boundaries

To effectively mitigate contract management risks, it is essential to design a standardized contract template that includes clauses for tracing raw material quality. This template should clearly specify the quality standards for raw materials, inspection methods, and the responsibilities suppliers must bear, ensuring swift identification of the source in case of quality issues. Simultaneously, establishing a supply chain responsibility matrix clearly delineates the roles and responsibilities of all parties involved in the raw material supply process. For instance, suppliers are responsible for providing raw materials that meet quality requirements and submitting relevant quality certification documents, while the mixing plant is responsible for inspecting and receiving the materials, promptly reporting any quality issues to suppliers. Through this dynamic delineation of responsibility boundaries, not only can contract management risks be reduced, but collaborative management efficiency can also be enhanced, ensuring the normal operation of the concrete mixing plant [9].

5.1.2. Digital transformation of performance evaluation

Developing a contract execution status dashboard system integrated with blockchain-based smart contracts for progress payments is a critical measure for enhancing collaborative management mechanism innovation, mitigating contract management risks, and promoting the digital transformation of performance evaluation. The contract execution status dashboard system enables real-time monitoring of contract progress, providing all parties with a clear overview of the contract status, facilitating the timely identification and resolution of potential issues, and reducing contract management risks. Meanwhile, blockchain-based smart contracts for progress payments offer a safer, more transparent, and efficient method for fund disbursements. They ensure accurate execution of payment conditions, eliminate interference from human factors, and provide immutable records, offering reliable data support for performance evaluation and advancing the digital transformation of performance evaluation [10].

5.2. Information management platform construction

5.2.1. Big data center development

In the technical management of concrete mixing plants, innovations in collaborative management mechanisms, information management platform construction, and big data center development are crucial. By establishing an operational data platform for the mixing plant, centralized management and analysis of various data types are achieved. Integrating ERP systems with GPS vehicle scheduling data streams enables the fusion of enterprise resource planning and transportation scheduling information. This allows real-time tracking of dynamic data across raw material procurement, production planning, and product delivery, while also leveraging big data analytics to identify potential issues and optimization opportunities. For instance, optimizing delivery routes based on transportation data enhances efficiency, and adjusting raw material ratios based on production data improves product quality. Additionally, the data platform provides a unified data interface for all departments, fostering interdepartmental collaboration, breaking down information silos, and ultimately enhancing overall operational efficiency and quality.

5.2.2. Intelligent decision support system

In terms of collaborative management mechanism innovation, establishing a cross-departmental communication and collaboration mechanism is essential to ensure seamless coordination across all stages of the concrete mixing plant. The construction of an information management platform should encompass raw material information, production process data, and quality inspection results, enabling real-time data collection and sharing. The intelligent decision support system should integrate root cause analysis algorithms for quality fluctuations and digital twin models for capacity optimization. By analyzing large volumes of production data, the root cause analysis algorithm precisely identifies the sources of quality issues, providing a basis for improvements. The capacity optimization digital twin model simulates various production scenarios, predicts capacity changes, and assists in formulating rational production plans, thereby enhancing production efficiency and quality stability, ultimately achieving efficient and high-quality operations of the concrete mixing plant.

5.3. Integrated service model innovation

5.3.1. Cross-professional collaboration mechanism

The technical management of concrete mixing plants involves multiple professional domains, necessitating innovative collaborative management mechanisms and integrated service models to strengthen cross-professional collaboration. Designing a seamless integration process between project management and engineering supervision duties is critical, clearly defining the responsibilities and handover points at each stage to avoid management gaps. Simultaneously, establishing a joint conference system for knowledge sharing is essential, periodically convening professionals from the mixing plant technology, engineering management, and quality supervision. During these meetings, participants share technological innovations and quality control experiences, and discuss solutions to practical issues. Through this cross-professional collaboration mechanism, information barriers are dismantled, facilitating the integration of diverse professional knowledge, enhancing the overall technical management level of the mixing plant, and achieving dual improvements in quality and efficiency.

5.3.2. Resource integration and value-added paths

In the technical management of concrete mixing plants, innovation in collaborative management mechanisms is crucial. An industrial alliance covering collaborative waste disposal can be established to achieve resource sharing and complementary advantages through cooperation among various parties. In terms of innovation in integrated service models, a green supply chain evaluation system should be built to assess the entire process from raw material procurement to product delivery, ensuring environmental friendliness and reliable quality. The path of resource integration and value addition lies in making full use of resources such as waste, applying them reasonably in concrete production, reducing costs while improving the environmental performance of products. Through these innovative measures, mixing plants can achieve sustainable development while improving quality and efficiency, and better adapt to market competition and environmental protection requirements.

6. Conclusion

The technical management of concrete mixing plants is crucial for enhancing quality and efficiency. Through systematic analysis of innovative pathways and validation of the application value of the whole-process engineering consulting model, significant results have been achieved. The synergistic optimization of the six major management systems has demonstrated a powerful impact, substantially improving production efficiency and significantly reducing quality incident rates. This not only provides strong support for the actual operation of mixing plants but also offers valuable references for industry development. Meanwhile, future research directions are clear: optimizing intelligent scheduling algorithms will further enhance the intelligence level of production, while establishing a carbon emission accounting system aligns with environmental requirements, contributing to the sustainable development of mixing plants. These research outcomes and future directions will collectively drive continuous progress in the technical management of concrete mixing plants, achieving higher efficiency and greater social benefits while ensuring quality.

Disclosure statement

The author declares no conflict of interest.

References

[1] Ouyang Z, 2021, Optimization of Tree Path Site Selection for Railway Engineering Concrete Mixing Plant, dissertation, East China Jiaotong University.

[2] Shang G, 2022, Design and Research of Intelligent Control System for Concrete Mixing Plant, dissertation, Jinan University.

[3] Wang G, 2021, Research on Product Image and Pollution Prevention Design of Concrete Mixing Plant, dissertation, Shandong University.

[4] Feng Y, 2021, Optimization of Performance Evaluation Index System for S Ready-Mixed Concrete Mixing Plant, dissertation, Suzhou University.

[5] Ding N, 2022, A Study on Improving the Service Quality of Elderly Care Institutions, dissertation, Guangdong University of Technology.

[6] Hu C, 2021, Exploration of Dust Pollution and Green Control Technologies in Concrete Mixing Plants. Engineering Construction and Design, (20): 95–97.

[7] Cen G, 2016, A Brief Discussion on the Reform of Technical Quality Management in Concrete Mixing Plants. Building Engineering Technology and Design, (20): 2614–2614.

[8] Chen L, 2018, On Quality Management of Commercial Concrete Mixing Plants. Building Materials and Decoration, (19): 130–131.

[9] Wang Z, 2015, Discussion on Quality Management of Commercial Concrete Mixing Plants. Theoretical Research on Urban Construction (Electronic Version), 5(14): 4055–4056.

[10] Chen Z, 2021, Discussion on Technical Quality Management of New Concrete Mixing Plant. Building Materials and Decoration, 17(8): 176–177.

Journal of Architectural Research and Development, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Prediction of Frozen Soil Deformation Characteristics Using Fractional Derivative Creep Model

Zhiheng Tian[1,2]*

[1]Future City Innovation Technology Co., Ltd., Shaanxi Construction Engineering Holding Group, Xi'an 710116, Shaanxi, China
[2]SCEGC-XJTU Joint Research Center for Future City Construction and Management Innovation, Xi'an Jiaotong University, Xi'an 710116, Shaanxi, China

**Author to whom correspondence should be addressed.*

Abstract: To investigate the temperature susceptibility and nonlinear memory effects of artificially frozen soil creep behavior, this study conducted uniaxial step-loading creep tests under controlled temperatures ranging from -10℃ to -20℃. The transient creep characteristics and steady-state creep rates of artificially frozen soils were systematically examined with respect to variations in temperature and stress. Experimental results demonstrate that decreasing temperatures lead to a decaying trend in the steady-state creep rate of silty frozen soil, confirming that low-temperature environments significantly inhibit plastic flow while enhancing material stiffness. Based on fractional calculus theory, a fractional derivative creep model was established. By incorporating temperature dependencies, the model was further improved to account for both stress and temperature effects. The model predictions align closely with experimental data, achieving over 91% agreement (standard deviation ± 1.8%), and effectively capture the stress-strain behavior of artificially frozen soil under varying thermal conditions. This research provides a reliable theoretical foundation for studying deformation characteristics in cold-regions engineering.

Keywords: Frozen soil; Fractional derivative; Creep deformation; Constitutive model

Online publication: October 10, 2025

1. Introduction

Driven by global climate change and the rapid development of cold-regions engineering, artificial ground freezing (AGF) technology has been extensively applied in metro connection passages, deep foundation pit support, and liquefied natural gas (LNG) storage tank foundations. As a critical supporting material in cold-regions underground engineering—including frozen construction methods and subsurface energy storage—the mechanical properties of artificially frozen soils, particularly their creep deformation behavior, directly govern the long-term stability and safety of structures. However, conventional integer-order creep models fail to accurately characterize the nonlinear deformation features and temperature susceptibility of frozen soils under low-temperature conditions, especially in capturing precise constitutive relationships under multiphysics field coupling.

Creep in artificially frozen soils exhibits marked nonlinearity, time-dependency, and temperature sensitivity. Its deformation mechanisms involve multiphysics coupling processes, including ice crystal redistribution, unfrozen water migration, and ice-soil skeleton interactions. Traditional integer-order models (e.g., Maxwell, Kelvin-Voigt, Burgers) can describe elastic and viscous responses but inadequately represent nonlinear memory effects and temperature-dependent characteristics during the attenuation creep stage. This theoretical limitation leads to insufficient prediction accuracy for long-term deformation in engineering practice, potentially causing safety hazards such as overdesigned freeze-wall thickness or support structure instability. Consequently, developing creep models that quantify thermo-stress coupling effects has become a priority in frozen soil mechanics.

Early frozen soil creep research primarily employed empirical and semi-empirical models. The Norton power-law model introduces a stress exponent to describe steady-state creep phase but fails to capture transient creep features [1]. While the Burgers model separates elastic, viscoelastic, and viscous deformation components, its linear superposition hypothesis deviates significantly from the nonlinear attenuation behavior characteristic of frozen soil creep. With advances in micromechanics and damage mechanics, scholars have attempted to enhance constitutive equations by incorporating damage variables. Fish's frozen viscoplastic model pioneered the inclusion of temperature as an independent variable [2]. However, its Arrhenius-type viscosity coefficient applies only to steady-state creep and does not account for strain hardening during transient stages.

Recently, fractional calculus has emerged as a powerful tool for describing non-integer-order dynamics due to its mathematical advantages in characterizing material heredity. Podlubny demonstrated that fractional derivatives inherently represent stress relaxation and creep history dependence through memory kernel functions, thereby providing new avenues for frozen soil creep modeling [3]. Wang *et al.* applied a fractional Scott-Blair model to analyze frozen clay creep, revealing a negative correlation between the fractional order α and unfrozen water content [4]. However, their model does not explicitly account for the influence of temperature gradients on α, limiting its engineering applicability.

To address these challenges in deformation regulation of artificially frozen soils under coupled thermal-mechanical fields, this study proposes a fractional derivative creep model capable of describing three-stage deformation processes (attenuation, steady-state, and accelerated creep) through a multiscale methodology integrating laboratory testing, numerical simulation, and field monitoring.

2. Uniaxial creep testing of artificially frozen soils

2.1. Experimental program

Soil specimens were retrieved from a cold-regions engineering site in Inner Mongolia, China, at depths of 15–20 m using core drilling equipment. The extracted frozen soil blocks were sealed in double-layer plastic bags and transported under refrigerated conditions (-30°C to -1°C) to the laboratory. After drying and pulverizing the undisturbed soil, specimens were reconstituted at 18.5% water content through compaction molding, forming cylindrical samples of 50 mm diameter × 100 mm height. These were subsequently flash-frozen at -30°C for 46 hours, followed by 24-hour isothermal curing at target test temperatures.

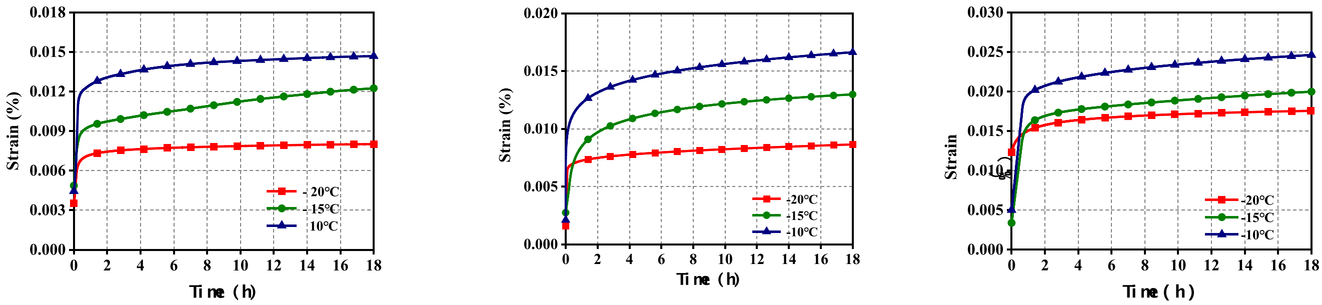
Uniaxial creep tests were conducted using a servo-hydraulic universal testing machine (UTM). Testing was performed at a baseline temperature of -10°C with extensions to -15°C and -20°C. A three-stage loading protocol was implemented by applying constant stresses at creep loading coefficients of $\sigma_c = 0.3\sigma_s$, $0.5\sigma_s$, $0.7\sigma_s$, where σ_s denotes the uniaxial compressive strength of frozen soil. Experimental data were acquired and strain-time curves were plotted, which enabled the quantitative analysis of how stress levels and test temperatures influence the creep behavior of frozen soils.

2.2. Experimental results

(1) Under constant stress conditions, the instantaneous strain of frozen soil increases significantly with rising temperature. For example, when the temperature increased from -20°C to -10°C, instantaneous strain rose by approximately 2.56 times (**Figure 1**). This results from elevated unfrozen water content, reduced viscosity at ice crystal interfaces, and weakened soil skeleton stiffness, collectively accelerating the initial elastic deformation response [5].

(2) At constant temperature (-20°C), creep deformation amplifies progressively with increasing stress levels, exhibiting intensified growth rates. When the loading coefficient reached 0.7, the maximum creep strain exceeded that at 0.3 by over 150%. This indicates significantly enhanced plastic flow in the ice matrix and shear-slip effects of unfrozen water films under high-stress conditions [6].

(3) Creep behavior under varying conditions demonstrates three distinct stages: (a) Attenuation creep stage: During initial loading, elastic deformation of the ice skeleton dominates. Creep rate decays exponentially with time, decreasing by ~40% per 5°C temperature increase. (b) Steady-state creep stage: Viscous flow of unfrozen water films and plastic slip of ice crystals reach dynamic equilibrium, stabilizing the creep rate. Steady-state rate correlates negatively with temperature and positively with stress (e.g., 30% higher at -10°C vs. -20°C). (c) Accelerated creep stage: Under high stress or elevated temperatures, microcrack propagation triggers chain damage mechanisms, causing creep rate to surge until failure. Here, the long-term strength limit and creep failure time obey a logarithmic correlation.



(a) $\sigma_c = 0.3\sigma_s$ (b) $\sigma_c = 0.5\sigma_s$ (c) $\sigma_c = 0.7\sigma_s$

Figure 1. Strain-time curves under constant stress conditions at varying temperatures

3. Parameter calibration for the fractional derivative creep model

3.1. Fractional derivative constitutive model for creep behavior

Under one-dimensional conditions, the creep strain of frozen soil can be expressed as:

$$\varepsilon_c = F\left(\sigma, T, t\right) \quad (1)$$

where ε_c represents the creep strain variable, and F denotes a function of stress (σ), temperature (T), and time (t).

To simplify the model, assuming decoupled effects of stress, temperature, and time, Equation (1) can be decomposed into:

$$\varepsilon_c = \sum_{i=1}^{n} f_i\left(T\right) g\left(\sigma\right) h\left(t\right) \quad (2)$$

Based on experimental results of frozen soil creep, the time-hardening theory was adopted to characterize creep behavior. This theory postulates that hardening is primarily governed by time and independent of accumulated deformation. Thus, the creep rate at constant temperature is expressed as:

$$\dot{\varepsilon}_{cr} = An\sigma^{m}t^{n-1} \tag{3}$$

where A is a material constant, n the stress exponent, and m the time decay exponent.

Assuming linear elastic instantaneous strain, integration of Equation (3) yields total strain:

$$\varepsilon_c = \varepsilon_{ct} + \varepsilon_{cr} = A + \int_0^t d\varepsilon_c = A + B\sigma_0^m t^n \tag{4}$$

where ε_c is the total strain, ε_{ct} the elastic strain, ε_{cr} the creep strain, and A, B, m, n are creep parameters.

It is evident that while this model accounts for load magnitude and creep effects, it fails to incorporate the influences of stress level and temperature level. Given that deformation in cold-regions engineering structures primarily arises from irreversible damage to the ice matrix under warming conditions, and considering the substantial temperature dependence of frozen soil creep behavior, we introduce stress level λ and temperature level θ. Consequently, an enhanced model incorporating these factors is formulated based on Equation (4), expressed as:

$$\varepsilon_c = \frac{\sigma}{E} + \lambda^k \times \theta \times \frac{t^{1-m}}{1-m} \tag{5}$$

$$\lambda = \frac{\sigma}{\sigma_c} \tag{6}$$

$$\sigma_c = \sigma_0 \times e^{(-\alpha(T-T_0))} \tag{7}$$

$$\theta = \frac{1}{1+\beta(T-T_{ref})} \tag{8}$$

where k is the stress coupling exponent, quantifying the nonlinear strengthening effect of stress level on creep rate; σ_c denotes the long-term strength of frozen soil; σ_0 represents the long-term strength at reference temperature T_0; α is the temperature sensitivity coefficient; β is the temperature decay coefficient; T_{ref} is the reference temperature.

3.2. Model parameter calibration

Long-term deformation of frozen soils is synergistically controlled by environmental temperature and stress levels, necessitating a fractional derivative creep model that concurrently captures stress thresholds and temperature sensitivity. In Equation (6) quantifying stress effects, σ_c represents the critical threshold for progressive damage within the ice matrix. Regarding temperature dependency in Equation (8), -10°C was selected as the reference temperature (T_0). To preserve the brittle-elastic characteristics of the ice skeleton, the instantaneous strain term is retained in the model. Parameter k governs ice crystal redistribution kinetics, while m characterizes the nonlinear influence of stress on unfrozen water film thickness.

Parameters α, β, k, and m were determined by curve-fitting experimental creep data under varying temperatures and stress levels. Values of α and β were calibrated through regression analysis of creep deformation against stress level λ and temperature level θ, as illustrated in **Figure 2**. Parameters k and m were obtained via multivariate least-squares fitting implemented in Python, with detailed results provided in **Table 1**.

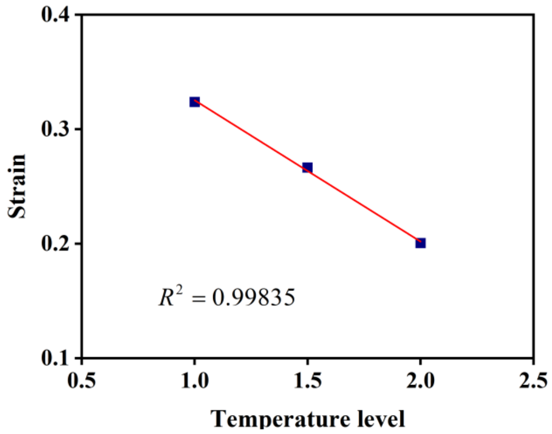


Figure 2. Relationship between creep strain and temperature level

Table 1. Model parameters fitting results

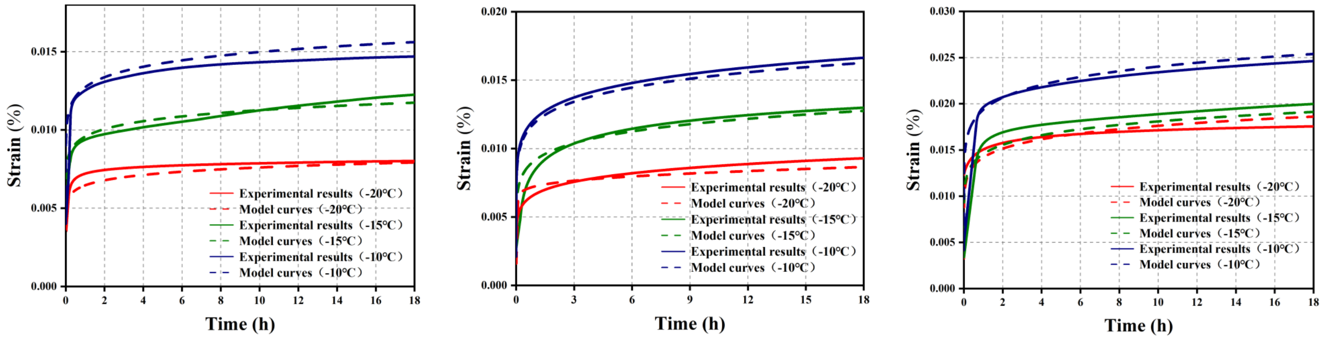
Temperature/°C	Loading coefficients	α	k	β	m
	0.3	0.55	0.05	1.62	0.21
-10	0.5	0.33	0.09	2.20	0.30
	0.7	0.17	0.11	2.25	0.12
	0.3	0.72	0.05	1.83	0.78
-15	0.5	0.42	0.09	2.14	0.46
	0.7	0.17	0.12	2.15	0.25
	0.3	0.72	0.08	1.82	0.78
-20	0.5	0.62	0.09	2.35	0.67
	0.7	0.27	0.05	2.15	0.41

3.3. Validation of fractional derivative creep model

Parameters from **Table 1** were substituted into Equation (5) to predict creep deformation of frozen soil under loading coefficients of 0.3, 0.5, and 0.7 using the fractional derivative creep model. As illustrated in **Figure 3**, close agreement exists between model predictions and experimental data, achieving an average goodness-of-fit of 91.9% (standard deviation: ±1.8%). This demonstrates the model's capability to effectively capture the creep behavior of frozen soils under varying thermo-mechanical conditions.

The model's high fitting accuracy stems from its mechanistic characterization of frozen soil creep deformation. Specifically, the temperature level θ couples temperature sensitivity, thereby quantifying the thickening effect of unfrozen water films [7]. The stress level λ captures the damage accumulation threshold, simulating accelerated propagation of ice crystal fractures to predict strain rate jumps. As λ increases, deformation rates during both attenuation and steady-state creep stages rise over time, causing the curve to approach an upward-sloping line. Crucially, λ governs the proportional durations of the three creep stages, manifesting as: (a) shortened steady-state creep duration, (b) earlier transition to accelerated creep, and consequently (c) extended acceleration periods.

Consequently, the fractional derivative creep model proposed herein accurately characterizes the full three-stage creep behavior—encompassing attenuation, steady-state, and accelerated creep—demonstrating broad applicability in permafrost engineering.



(a) $\sigma_c = 0.3\sigma_s$ (b) $\sigma_c = 0.5\sigma_s$ (c) $\sigma_c = 0.7\sigma_s$

Figure 3. Comparison between experimental results and model curves for frozen soil creep

4. Conclusion

To characterize creep deformation behavior of frozen soils, this study establishes an enhanced fractional derivative creep model incorporating coupled stress level λ and temperature reduction factor θ, based on uniaxial creep tests. Validated against experimental data through multivariate least-squares fitting, the model demonstrates both applicability and accuracy. The major findings are given as follows.

(1) The fractional derivative creep model achieves >91% average goodness-of-fit with experimental data. Consistent strain evolution patterns and robust performance across broad stress ranges and thermal conditions confirm its reliability for engineering deformation prediction.

(2) By introducing dual parameters λ (stress level) and θ (temperature reduction factor), the model quantifies stress-temperature coupling effects, accurately capturing stress-threshold behavior and temperature sensitivity. This enables precise characterization of full three-stage creep deformation.

(3) The model overcomes limitations of conventional empirical approaches where parameters lack physical significance due to pure curve-fitting. By explicitly incorporating thermo-mechanical controls, it exhibits enhanced generalizability for engineering applications.

Funding

National Key Research and Development Program of China "Structural Stability Assessment Techniques and Demonstration for Masonry Ancient Pagodas" (2023YFF0906005)

Disclosure statement

The author declares no conflict of interest.

References

[1] Zhao X, Zhou G, 2013, Experimental Study on the Creep Behavior of Frozen Clay with Thermal Gradient. Cold Regions Science and Technology, 86: 127–132.

[2] Fish AM, 1983, Mathematical Models of Soil Freezing. CRREL Report, 83: 13.

[3] Podlubny I, 1999, Fractional Differential Equations. Mathematics in Science and Engineering, 198: 41–119.

[4] Wang X, Li D, 2020, Fractional Derivative Modeling of Creep Behavior for Frozen Soil. Mechanics of Time-Dependent Materials, 24(3): 287–302.

[5] Yang S, Wang N, Zhang H, 2020, Study on Creep Test and Creep Model of Warm Frozen Soil. Journal of Glaciology and Geocryology, 42(3): 834–842.
[6] Song YJ, Zhang LT, Ren JX, et al., 2021, Triaxial Creep Properties and Model of Red Sandstone under Freeze-Thaw Environment. Chinese Journal of Geotechnical Engineering, 43(5): 841–849.
[7] Wang Z, Li J, Teng J, et al., 2023, THM Coupled Model for Simulating Frost Heave Based on a New Water Film Pressure Criterion. Chinese Journal of Geotechnical Engineering, 45(5): 997–1007.

Journal of Architectural Research and Development, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Research on Modular Design, Production, and Construction Integration of Municipal Prefabricated Bathroom Stations

Qiang Huang*

Shenzhen 518000, China

**Author to whom correspondence should be addressed.*

Abstract: This article focuses on the municipal prefabricated bathroom station. It elaborates on its modular design concept, including key design points such as spatial layout, functional modules, and determination of key parameters; introduces the optimization of intelligent production processes, precision control, and integration of construction technology, and also mentions the verification of full lifecycle applications and quality control; as well as emphasizes the importance of BIM + IoT platform and looks forward to the future.

Keywords: Municipal prefabricated; Bathroom station; Modular design

Online publication: October 10, 2025

1. Introduction

With the acceleration of urbanization, the demand for municipal infrastructure construction continues to increase. The *Guiding Opinions on Promoting the Coordinated Development of Intelligent Construction and Building Industrialization*, issued by China in 2020, emphasized the importance of building industrialization and the application of intelligent technology in it. As a part of urban infrastructure, the design and construction of municipal prefabricated bathroom stations have received widespread attention. This study focuses on the municipal prefabricated bathroom stations, starting from the modular design concept, exploring key design parameter determination, intelligent production process optimization, precision control, construction technology integration, and full lifecycle application verification, aiming to improve its design efficiency, production quality, construction accuracy, and operation and maintenance management level to meet the needs of urban development and provide better public service facilities for urban residents.

2. Construction of a modular design system

2.1. Modular design concept

The modular design concept is the core guiding principle for the design of municipal prefabricated bathroom stations. It emphasizes the decomposition of the overall space into multiple modules with specific functions, which are both independent of each other and can be organically combined to meet different scenarios and user needs. By standardizing the spatial layout design, the overall structure of the bathroom station and the size and location of each functional area are consistent and standardized, improving design efficiency and replicability. The universal design of functional modules emphasizes the universality and interchangeability of modules, ensuring that modules with similar functions in different projects can be used interchangeably and reducing production costs. At the same time, the integration of ergonomic design points makes each module more in line with the physiological and psychological needs of the human body, improving user comfort and satisfaction [1]. Combining BIM technology to establish a parametric model library, further optimizing module design and assembly processes, and achieving visualization and precision in design.

2.2. Determination of key design parameters

The determination of key design parameters is crucial in the modular design of municipal prefabricated bathroom stations. For structural systems, it is necessary to consider load combination conditions for optimized design. Different usage scenarios and geographical locations can lead to varying load situations. By accurately analyzing various possible load combinations, such as live loads, wind loads, snow loads, etc., the bearing capacity and stability requirements of the structure can be reasonably determined. Research on integrated design methods is crucial in the areas of water supply, drainage, and electrical systems. It is necessary to clarify the connection methods and technical parameters between each component to ensure the efficient operation of the system. For example, the diameter and slope of water supply and drainage pipelines, as well as the voltage, current, and other parameters of electrical circuits, need to be accurately determined based on the actual needs of the station and the design of the module. At the same time, the clarification of standardized interface technical parameters for components is also an important part of achieving modular design, which ensures accurate connection and collaborative work between different modules [2].

3. Intelligent production process optimization

3.1. Construction of an intelligent manufacturing system

The development of a material management system based on the BOM list is the key to the construction of an intelligent manufacturing system in the optimization of the intelligent production process. In the selection of automated cutting equipment, it is necessary to comprehensively consider factors such as cutting accuracy, efficiency, and material adaptability to ensure that the high-quality requirements for the production of prefabricated bathroom stations are met. The modular mold matching scheme should be designed based on the standard modules of the product to improve the universality and reusability of the mold and reduce production costs [3]. The configuration of welding robot workstations should be based on the characteristics of production processes and welding tasks, and the number, model, and working parameters of robots should be reasonably determined to ensure the stability and consistency of welding quality, and to improve overall production efficiency and product quality.

3.2. Research on precision control technology

Establishing a critical dimension tolerance allocation model is an important foundation for precision control. By analyzing the dimensions of each module in the prefabricated bathroom relay station, considering the accumulation of errors in manufacturing and assembly processes, a reasonable allocation of tolerances is necessary to ensure the matching accuracy of each component during assembly [4]. The proposal of temperature deformation compensation technology is aimed at the influence of different environmental temperatures on materials and component dimensions. Study the temperature change law and adopt appropriate compensation methods, such as reserving expansion space or using temperature-adaptive materials, to reduce dimensional deviations caused by temperature changes. The development of a pre-assembly testing process allows for the pre-assembly of modules before formal assembly, promptly identifying and correcting issues such as dimensional discrepancies. At the same time, establish packaging protection standards for modular components to prevent component deformation caused by collisions, squeezing, etc., during transportation and storage, which may affect assembly accuracy.

4. Integrated assembly construction technology

4.1. Innovation in construction organization and management

4.1.1. Three-dimensional site layout technology

In the municipal prefabricated bathroom station project, three-dimensional site layout technology is crucial. The application of BIM + GIS technology enables precise modeling and analysis of construction sites. Through construction simulation, potential issues that may arise during the construction process can be understood in advance, such as unreasonable use of site space and obstruction of module transportation. At the same time, based on the simulation results, module transportation path planning is formulated to ensure efficient and safe transportation process, and avoid interference with the surrounding environment [5]. In addition, it is necessary to establish standards for site handover and acceptance, clarify the requirements for indicators such as site flatness and bearing capacity, and provide a good foundation for the installation of modular bathroom stations to ensure construction quality and progress.

4.1.2. Rapid assembly process development

In the integration of prefabricated construction technology, it is necessary to innovate construction organization management and develop rapid assembly processes. It is crucial to innovate the modular unit lifting timing control method for municipal prefabricated bathroom stations. By accurately planning the lifting sequence, construction efficiency can be improved, and construction time and costs can be reduced [6]. Meanwhile, the development of new node connection devices is a crucial step. This device should exhibit characteristics such as high strength, reliability, and ease of installation to ensure the stability and safety of the bathroom station structure. In addition, a construction quality control system should be established to strictly control the quality of node connections, including connection processes, material quality testing, etc., in order to ensure the quality and performance of the entire prefabricated bathroom station.

4.2. On-site integrated installation system

4.2.1. Comprehensive pipeline installation technology

Establishing a construction process for separating mechanical and electrical pipelines from structural bodies is the key to comprehensive pipeline installation technology. This process can prevent mutual interference between pipelines and structures in traditional construction and improve construction efficiency and quality [7]. The development of prefabricated support and hanger systems has further optimized pipeline installation. It is characterized by standardization and modularization, which can quickly and accurately install pipelines, and is easy to maintain and adjust in the later stage. Meanwhile, concealed engineering detection technology is also crucial. Through advanced detection technology, problems in concealed engineering can be detected in a timely manner, such as whether the connections of pipelines are tight, whether the installation of supports and hangers is firm, etc., ensuring the reliability and safety of the entire pipeline installation project.

4.2.2. Reserved intelligent operation and maintenance interface

In the on-site integrated installation system of prefabricated construction technology integration, the reservation of intelligent operation and maintenance interfaces is crucial. The reasonable arrangement of embedded parts for intelligent monitoring systems should be considered, which needs to be combined with the actual usage needs and functional zoning of bathroom stations to determine the optimal location of sensors and other monitoring equipment, in order to accurately obtain relevant data [8]. At the same time, standardized design specifications for equipment maintenance ports should be established, and the size, position, and opening method of the maintenance ports should be standardized to facilitate later equipment maintenance and repair. This can not only improve operation and maintenance efficiency but also reduce costs, ensuring that prefabricated bathroom stations maintain good performance and functionality during long-term use.

5. Full lifecycle application verification

5.1. Application analysis of demonstration projects

5.1.1. Typical project construction cases

In the study of municipal prefabricated bathroom stations, three types of municipal scenario demonstration projects were selected for analysis. By comparing the adaptability parameters of the site in different scenarios, it was found that there are differences in spatial utilization and integration with the surrounding environment. Meanwhile, research has been conducted on the optimization effect of the construction cycle, and the results show that the integration of prefabricated design and construction significantly shortens the construction cycle. For example, in a bustling commercial street scene with limited space and strict requirements for construction time, the prefabricated bathroom station was quickly assembled through reasonable module design, reducing the impact on surrounding commercial activities [9]. In the park setting, it better adapts to the natural environment, complements the landscape, and the construction process is efficient, further verifying the advantages of this integrated model in different municipal scenarios.

5.1.2. Full process benefit evaluation

Establish a comprehensive evaluation index system that includes carbon emissions, cost savings rate, and failure repair rate, and conduct a full process benefit evaluation of municipal prefabricated bathroom stations. The carbon emission index can measure its impact on the environment, reflected in the greenhouse gas emissions during material production, transportation, construction, and use [10]. The cost-saving rate reflects the economic advantages of modular integrated design, production, and construction compared to traditional methods, including savings in material costs, labor costs, and time costs. The failure repair rate is related to product quality and later maintenance costs, and a lower failure repair rate means higher reliability and durability. By comprehensively evaluating these indicators, we can gain a comprehensive understanding of the performance benefits of municipal prefabricated bathroom stations throughout their entire lifecycle, providing a basis for their further promotion and optimization.

5.2. Construction of key parameter database

5.2.1. Standardized component data module

The full lifecycle application verification requires the construction of a key parameter database and a standardized component data module. The formation of the standardized parameter table for size modulus serialization is the foundation, which should cover the key size parameters of various components of municipal prefabricated bathroom stations, ensuring compatibility and universality between different components. At the same time, establish component attribute coding rules to assign unique identity identifiers to each component, facilitating precise management by the information management platform. This information management platform integrates various attribute information of components, including design parameters, production processes, construction requirements, etc., to achieve data traceability and collaborative management of the entire process from design to construction, improve the efficiency and quality of the entire project, and provide strong support for the modular design, production, and construction integration of municipal prefabricated bathroom stations.

5.2.2. Construction deviation warning model

In the full lifecycle application verification, the construction of key parameter databases and construction deviation warning models is crucial. For the key parameter database, it is necessary to collect key data covering all stages of design, production, and construction, including material characteristics, component dimensions, installation requirements, etc. At the same time, it is necessary to ensure the accuracy and completeness of the data in order to provide a reliable basis for subsequent analysis.

Develop a machine learning-based 3D scanning deviation recognition algorithm for construction deviation warning models. Utilize 3D scanning technology to obtain actual data from the construction site, analyze the data through algorithms, and identify deviations from design standards. On this basis, an error accumulation propagation prediction model is constructed, considering the transmission and accumulation effects of errors during the construction process, to predict possible large deviations in advance, and take timely measures to adjust, ensuring the construction quality and accuracy of prefabricated bathroom stations.

5.3. Innovation of standardized management mechanism

5.3.1. PDCA quality control cycle

In the municipal prefabricated bathroom station project, the PDCA quality control cycle runs through the entire process. In the Plan phase, a detailed quality plan is developed based on project requirements, clarifying quality objectives and key control points for each stage of design, production, and construction. During the Do phase, design, production, and construction activities are carried out according to the established plan to ensure that each link meets quality requirements. During the Check phase, establish a three-stage quality traceability mechanism for design–production–construction, rigorously inspect key processes, and refer to the established visual acceptance standards for key processes to promptly identify quality issues. In the Act stage, effective measures are taken to address the identified issues, lessons learned are summarized, successful experiences are incorporated into standards and systems, deficiencies are improved, and reference is provided for subsequent projects to achieve continuous improvement in quality.

5.3.2. Development of a collaborative management platform

Building a multi-party collaborative work platform combining BIM and Internet of Things is the key to achieving full lifecycle management of municipal prefabricated bathroom stations. This platform integrates data from various stages of design, production, and construction, and provides accurate 3D models through BIM technology to visually display component information and assembly processes. The IoT technology enables real-time monitoring of component production, transportation, and on-site construction status. At the same time, the integrated quality traceability QR code system assigns a unique identification to each component. By scanning the QR code, users can obtain all information about components from raw material procurement to installation completion, including quality inspection reports, production batches, installation personnel, etc., ensuring quality traceability, improving standardized management level, and promoting efficient collaboration among all parties involved.

6. Conclusion

This study comprehensively explored the municipal prefabricated bathroom relay station. In terms of modular design, innovation has been achieved, optimizing space utilization and functional layout. Breakthroughs have been made in intelligent production technology, which has improved production efficiency and quality. The prefabricated construction process has been optimized, shortening the construction period and reducing the amount of on-site work. At the same time, the development direction of the operation and maintenance management system based on digital twin technology is proposed, which will provide more efficient and accurate support for later maintenance and management. Looking ahead to the future, modular buildings have broad prospects for promotion and application in the construction of new urbanization. They can meet the needs of rapid construction, energy conservation, and environmental protection, improve the level and quality of urban infrastructure construction, and provide more convenient and comfortable public service facilities.

Disclosure statement

The author declares no conflict of interest.

References

[1] Smith RE, 2010, Prefab Architecture: A Guide to Modular Design and Construction, John Wiley & Sons.

[2] Shroff DN, Joshi AT, 2022, Pre-Fabricated Architecture for Urban Adaptability: Factory Built Constructions–Sustainable & Flexible Urban Solutions, dissertation, Politecnico di Torino.

[3] Tembhurkar S, Ralegaonkar R, Azevedo A, et al., 2022, Low Cost Geopolymer Modular Toilet Unit for ODF India—A Case Study. Case Studies in Construction Materials, 16: e00937.

[4] Lawson M, Ogden R, Goodier CI, 2014, Design in Modular Construction, CRC Press, Boca Raton, FL.

[5] Vaz-Serra P, Wasim M, Egglestone S, 2021, Design for Manufacture and Assembly: A Case Study for a Prefabricated Bathroom Wet Wall Panel. Journal of Building Engineering, 44: 102849.

[6] Zhou JX, Shen GQ, Yoon SH, et al., 2021, Customization of On-Site Assembly Services by Integrating the Internet of Things and BIM Technologies in Modular Integrated Construction. Automation in Construction, 126: 103663.

[7] Boafo FE, Kim JH, Kim JT, 2016, Performance of Modular Prefabricated Architecture: Case Study-Based Review and Future Pathways. Sustainability, 8(6): 558.

[8] Issabayev G, Slyambayeva A, Kelemeshev A, et al., 2022, Development of the Project of Modular Prefabricated Buildings. EUREKA: Physics and Engineering, (4): 36–45.

[9] Lacey AW, Chen W, Hao H, et al., 2018, Structural Response of Modular Buildings—An Overview. Journal of Building Engineering, 16: 45–56.

[10] Jiang Y, Zhao D, Wang D, et al., 2019, Sustainable Performance of Buildings Through Modular Prefabrication in the Construction Phase: A Comparative Study. Sustainability, 11(20): 5658.

Journal of Architectural Research and Development, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Innovative Models for Construction and Pipeline Operation and Maintenance of Water Plants Driven by Smart Water Management

Jingyi Shi*

Shenzhen 518000, Guangdong, China

**Author to whom correspondence should be addressed.*

Abstract: This article elaborates on the application of smart water management in the construction of water plants and the operation and maintenance of pipeline networks, covering all layers of the technical framework, including IoT perception. It introduces full chain application scenarios, such as water source monitoring. It also involves BIM, intelligent IoT device applications, breakthroughs in pipeline monitoring system construction and operation technology, as well as the economic cost-effectiveness of innovative models, evaluation index systems, system iteration and upgrading strategies, and points out limitations and future development directions.

Keywords: Smart water management; Construction and operation and maintenance; Technical framework

Online publication: October 10, 2025

1. Introduction

With the continuous development of technology, smart water management has become an important direction for the water industry. The *14th Five-Year Plan for Building a Water Saving Society*, released in 2021, emphasizes the importance of efficient utilization of water resources and intelligent upgrading of water management systems, providing policy support for the development of smart water management. Smart water management covers the entire chain of application scenarios from water source monitoring to intelligent regulation of pipeline networks. Its technical framework includes multiple layers, such as the Internet of Things perception layer, 5G communication layer, cloud computing platform layer, AI algorithm layer, etc. The data center and digital twin technology play a key role. At the same time, BIM technology, intelligent IoT devices, and other technologies have important applications in intelligent construction management, laying the foundation for innovative models of water plant construction and pipeline operation and maintenance, and are of great significance for improving water supply quality and efficiency.

2. Smart water technology system and core features

2.1. Smart water technology framework

The smart water technology framework covers multiple levels. The IoT perception layer collects water data, such as water quality and quantity, through sensors and other devices [1]. The 5G communication layer ensures high-speed and stable data transmission, enabling the timely transmission of massive water data. The cloud computing platform layer provides powerful computing capabilities for storing and processing data. The AI algorithm layer utilizes intelligent algorithms to analyze and mine data. Among them, the data center plays a key role in integrating data by aggregating and standardizing data from different sources, providing a foundation for subsequent analysis and application. The digital twin technology constructs a virtual model of the water management system to achieve real-time mapping and simulation of the real water management system, which helps optimize the operation and management of the water management system, and improve the efficiency and quality of water plant construction and pipeline operation and maintenance.

2.2. Typical application scenarios of intelligence

Smart water management covers the entire chain of application scenarios from water source monitoring to intelligent control of pipeline networks. In terms of water source monitoring, sensors and other technologies are used to obtain real-time data on water quality and quantity, providing a basis for subsequent processing. The automation of water plants enables intelligent control of the production process, improving efficiency and water quality stability. Intelligent regulation of pipeline networks can optimize water supply scheduling based on real-time data, reducing energy consumption [2]. In terms of construction supervision, real-time monitoring of the construction process is carried out through intelligent devices and systems to ensure construction quality and safety. The operation and maintenance warning function can detect potential faults in the pipeline network in advance, take timely measures, reduce losses, and ensure the continuity and reliability of the water supply.

3. Innovative practice of intelligent construction management

3.1. BIM technology integration for construction supervision

BIM technology plays an important role in intelligent construction management. In terms of factory planning, BIM models can be used for 3D visualization, making the design scheme more intuitive and easier for construction personnel to understand and execute [3]. For pipeline collision detection, BIM technology can simulate the pipeline laying situation in advance, accurately identify possible collision points, and effectively avoid rework and resource waste during the construction process. By combining BIM with relevant digital technologies in construction progress monitoring, real-time project progress information can be obtained, and deviations can be detected and adjusted in a timely manner by comparing the planned progress. In terms of quality monitoring, BIM models can record in detail various parameters and quality acceptance situations during the construction process, providing a basis for quality traceability and problem investigation, ensuring that construction quality meets standards.

3.2. Innovation in the application of intelligent IoT devices

Intelligent IoT devices have important innovative applications in intelligent construction management. In terms of monitoring deep foundation pits, intelligent sensing devices such as displacement sensors and water level sensors installed on the side walls of the pit can obtain real-time key data like pit deformation and groundwater level, and transmit the data to the monitoring center [4]. For pipeline welding quality inspection, intelligent testing equipment can be used to accurately determine the quality of the welding area through non-destructive testing techniques such as ultrasonic testing, radiographic testing, etc., and provide real-time feedback on the results. Meanwhile, it is crucial to establish a mechanism for device data collection and early warning response. The collected data needs to be analyzed in real-time. When the data exceeds the set threshold, the system will automatically issue a warning, and relevant personnel can take timely measures to ensure construction safety and quality.

4. Breakthrough in intelligent operation and maintenance technology for pipeline networks

4.1. Construction of a real-time monitoring system for the pipeline network

4.1.1. Layout of multi-source perception network

Under the drive of smart water management, it is crucial to build a multi-source perception network layout for real-time monitoring of pipeline networks. A three-dimensional layout plan that includes pressure, flow, and noise sensors should be designed. By properly arranging these sensors, key data on the operation of the pipeline network can be comprehensively obtained. For example, pressure sensors can monitor changes in pipeline pressure, flow sensors can measure water flow conditions, and noise sensors can help detect potential anomalies. At the same time, it is necessary to establish installation standards for online water quality monitoring terminals to ensure their accurate monitoring of water quality conditions. Through such a multi-source perception network layout, comprehensive and accurate data support can be provided for intelligent operation and maintenance of the pipeline network, achieving real-time and accurate monitoring of the operation status of the pipeline network, laying the foundation for innovative models of water plant construction and pipeline operation and maintenance [5].

4.1.2. Data transmission and cleaning mechanism

In the breakthrough of intelligent operation and maintenance technology for pipeline networks, the construction of a real-time monitoring system for pipeline networks is crucial. Real-time collection of key parameters of the pipeline network, such as pressure, flow rate, water quality, etc., is done through various sensors [6]. The data transmission and cleaning mechanism is the key to ensuring the effectiveness of monitoring data. Utilizing advanced communication technologies, such as building a hybrid network solution of NB IoT and LoRa, can achieve efficient and stable data transmission. For the collected data, due to possible issues such as noise and outliers, it is necessary to develop an anomaly recognition algorithm based on time series for cleaning. This algorithm can accurately identify data points that do not conform to normal patterns, improve data quality, and provide reliable data support for subsequent pipeline status analysis and operation decisions.

4.2. Intelligent diagnosis technology for pipeline leakage

4.2.1. Hydraulic model and AI fusion diagnosis

Combining the EPANET hydraulic model with an LSTM neural network to establish an intelligent diagnosis system for pipeline pressure anomalies can effectively improve the efficiency of pipeline operation and maintenance. The EPANET hydraulic model can accurately simulate the water flow state and pressure distribution in the pipeline network [7]. LSTM neural networks have the advantage of processing time series data and can learn and analyze pipeline pressure data. By integrating the two, the system can utilize the physical laws provided by hydraulic models and the learning ability of LSTM neural networks to diagnose pressure anomalies more accurately. This system can monitor the pressure of the pipeline network in real time, detect potential leakage points or other faults in a timely manner, provide strong support for the intelligent operation and maintenance of the pipeline network, and reduce the waste of water resources and economic losses.

4.2.2. Acoustic detection and positioning system

Develop a leakage voiceprint recognition algorithm based on convolutional neural networks, which can accurately identify different types and degrees of leakage voiceprint features through learning and analysis of a large number of leakage sound samples [8]. At the same time, by integrating GIS systems and utilizing their powerful geographic information processing capabilities, leak locations can be combined with geographic spatial information. The leakage voiceprint information identified through algorithms is accurately matched and located in GIS systems, thereby achieving fast and accurate determination of the location of pipeline leaks. This integrated system not only improves the accuracy of leak diagnosis but also provides accurate location information for subsequent repair and maintenance work, greatly improving the efficiency and quality of pipeline operation and maintenance.

5. Application verification of innovative models

5.1. Typical engineering case analysis

5.1.1. Project background and problem diagnosis

The renovation project of a smart water plant in a certain city is typical. The original pipeline network system faces many problems, and frequent pipe bursts are one of the prominent difficulties. This not only affects the continuity of water supply, but also increases maintenance costs and water resource waste [9]. Meanwhile, fluctuations in water quality also pose hidden dangers to residents' water safety, possibly due to aging and corrosion of the pipeline network, as well as a lack of effective water quality monitoring and control measures. These problems seriously constrain the stability and reliability of urban water supply, and there is an urgent need for innovative construction and operation modes to improve the operational efficiency and water supply quality of water plants.

5.1.2. Implementation path of intelligent systems

The implementation path of intelligent systems is crucial in the innovative mode of water plant construction and pipeline operation and maintenance driven by smart water management. The construction of a digital twin platform requires the integration of multiple sources of data, including water plant facility parameters, pipeline network topology, and operational data, to build an accurate virtual model [10]. The deployment of intelligent equipment should be based on the actual needs of the water plant and pipeline network, and intelligent sensors, automation control equipment, etc., should be selected and installed reasonably to achieve real-time monitoring and control of key indicators such as water quality, water quantity, and water pressure. During the system integration phase, it is necessary to ensure smooth data exchange between the digital twin platform and intelligent devices, optimize the system by simulating different operating conditions, improve the operational efficiency of the water plant and the level of pipeline operation and maintenance, and ensure safe and stable water supply.

5.2. Multidimensional evaluation of application effectiveness

5.2.1. Economic cost-benefit analysis

The application of smart water management mode in the construction of water plants and the operation and maintenance of pipeline networks has brought significant economic cost-effectiveness. From the perspective of cost structure, the traditional model accounts for a relatively large proportion of human and material resource consumption, while the smart model has a significant reduction in operation and maintenance labor costs in the later stage, despite the initial investment in technology and equipment. For example, intelligent monitoring devices can provide real-time feedback on pipeline operation data, reducing the frequency of manual inspections. In terms of the investment return cycle, through precise calculation, considering equipment procurement, installation, and commissioning, and later operation and maintenance costs, combined with the water-saving and economic benefits brought by reducing leakage, the smart model can achieve cost recovery and start to make profits after a certain operating period. The water-saving benefits are significant. Through real-time monitoring and precise regulation, water resource waste can be effectively reduced, bringing not only economic value but also environmental and social benefits.

5.2.2. Comprehensive evaluation of social benefits

By establishing an evaluation index system that includes water supply stability, emergency response speed, and public satisfaction, a comprehensive evaluation of innovative models driven by smart water management is conducted. In terms of water supply stability, monitoring data shows that after the application of innovative models, the range of water pressure fluctuations has decreased, and the water quality compliance rate has significantly improved, ensuring stable water use for residents. In terms of emergency response speed, with the help of intelligent monitoring and warning systems, fault location is more accurate, and the time for maintenance teams to arrive at the scene is significantly reduced, minimizing losses caused by water supply interruptions. The results of the public satisfaction survey indicate that residents' satisfaction with water quality, water supply stability, and service response has all increased. From the comprehensive evaluation of social benefits, this innovative model not only improves the operational efficiency and service quality of water plants but also helps to save water resources, reduce social conflicts caused by water supply problems, and has positive significance for urban sustainable development.

5.3. Technical optimization and mode innovation

5.3.1. System iteration upgrade strategy

The distributed model optimization scheme based on federated learning is of great significance in the system iteration and upgrading strategy of smart water management. Through this scheme, data sharing and model training among multiple nodes can be achieved while protecting data privacy. Its advantage lies in the ability to integrate information from different data sources, improving the accuracy and generalizability of the model.

The data storage application of blockchain technology also provides new ideas for smart water management. It ensures the immutability and traceability of data, and can play a key role in water quality monitoring data, pipeline operation and maintenance records, and other aspects. For example, when water quality problems arise, accurately tracing the data records of relevant links can help quickly locate the root cause of the problem, ensure water supply safety, and promote the continuous optimization and upgrading of innovative models for water plant construction and pipeline operation and maintenance.

5.3.2. Standardized construction of operation and maintenance mode

The development of an enterprise standard framework for smart water construction and operation is the core. Clear standards need to be established in terms of construction process, equipment selection and installation, system integration, etc., to ensure construction quality and system compatibility. For example, specifying the construction process parameters for different pipe diameter pipelines in detail. In terms of operation and maintenance, it should cover equipment maintenance cycles, fault diagnosis processes, data monitoring indicators, and other related content. Taking equipment maintenance as an example, develop detailed maintenance schedules and operation guidelines for various types of equipment. At the same time, attention should be paid to the operability and dynamic updating of standards, and timely adjustments and optimizations should be made with the development of technology and the accumulation of practical experience. The formed business promotion model should be based on a standard framework, highlighting advantages and benefits, such as improving operation and maintenance efficiency, reducing costs, etc., attracting more enterprises to adopt, and achieving the widespread application of smart water management models.

6. Conclusion

Smart water management has achieved significant results in the construction and operation of water treatment plants, including improving construction quality and operation efficiency. However, the current technology system has some limitations, such as insufficient edge computing capabilities and model generalization capabilities. Looking ahead to the future, the deep integration of digital twins and metaverse technology will bring new development directions for smart water management. Digital twins can accurately simulate real water systems by constructing virtual models, providing decision support for construction and operation. Metaverse technology can further enhance the immersion and interactivity of virtual environments, optimizing the operational experience of construction and operation. This integration is expected to break through the limitations of existing technologies and promote more efficient and intelligent innovative development of smart water management in the fields of water plant construction and pipeline operation and maintenance.

Disclosure statement

The author declares no conflict of interest.

References

[1] Boulos PF, 2017, Smart Water Network Modeling for Sustainable and Resilient Infrastructure. Water Resources Management, 31(10): 3177–3188.

[2] Gade DS, 2021, Reinventing Smart Water Management System Through ICT and IoT-Driven Solution for Smart Cities. International Journal of Applied Engineering and Management Letters, 5(2): 132–151.

[3] Lee SW, Sarp S, Jeon DJ, et al., 2015, Smart Water Grid: The Future Water Management Platform. Desalination and Water Treatment, 55(2): 339–346.

[4] Ramos HM, 2022, Innovations in Water Management: Systems Efficiency and Energy Applications in the Water Sector, The Palgrave Handbook of Global Sustainability, Springer International Publishing, Cham, 1–32.

[5] Palermo SA, Maiolo M, Brusco AC, et al., 2022, Smart Technologies for Water Resource Management: An Overview. Sensors, 22(16): 6225.

[6] Dogo EM, Salami AF, Nwulu NI, et al., 2019, Blockchain and Internet of Things-Based Technologies for Intelligent Water Management System. Artificial intelligence in IoT, 2019: 129–150.

[7] Gupta AD, Pandey P, Feijoo A, et al., 2020, Smart Water Technology for Efficient Water Resource Management: A Review. Energies, 13(23): 6268.

[8] Ramos HM, McNabola A, Lopez-Jimenez PA, et al., 2019, Smart Water Management Towards Future Water Sustainable Networks. Water, 12(1): 58.

[9] Giudicianni C, Herrera M, Nardo A, et al., 2020, Overview of Energy Management and Leakage Control Systems for Smart Water Grids and Digital Water. Modelling, 1(2): 134–155.

[10] Li J, Yang X, Sitzenfrei R, 2020, Rethinking the Framework of Smart Water System: A Review. Water, 12(2): 412.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Journal of Architectural Research and Development, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Foreign Dominance and Local Resilience in Infrastructure Development: Evidence from Sarawak, East Malaysia

Yongqiang Wu[1]*, Jinqiao Ling[2]

[1]Graduate School of Business, SEGi University, Kuala Lumpur 47810, Malaysia
[2]Jianxi Environmental Engineering Vocational College, Ganzhou 341000, China

**Author to whom correspondence should be addressed.*

Abstract: As the Sarawak state government accelerates infrastructure development to stimulate economic growth, it has attracted numerous foreign construction enterprises—particularly Chinese firms—entering the market through low-cost bidding. However, this foreign-dominated model, while improving efficiency, has triggered local enterprise marginalization, industrial chain fragmentation, payment delays, and project setbacks, undermining the intended economic spillover effects of public investment. Grounded in policy analysis and field evidence within a dependency theory framework, this study evaluates the structural impacts of foreign participation on Sarawak's local economy, uncovers governance gaps, and proposes strategies to enhance local economic resilience under open-market conditions. The findings reveal that foreign contractors (especially Chinese enterprises), despite their capital and technological advantages in dominating mega-projects, exhibit pervasive shortcomings: inadequate local participation (falling far below the 40% policy target), deficient knowledge transfer (local firms hold only 6% of green technology patents), significant value leakage (foreign profit repatriation dominated project value flows), and widespread execution delays/cost overruns due to underestimation of tropical climate-geological risks, institutional maladaptation, and resource misallocation. Drawing on experiences from the Philippines, Indonesia, and Vietnam, the study proposes systemic reforms: introducing a Low-Bid Risk Evaluation System (LRES), enforcing a mandatory Local Participation Index (LPI), establishing a Smart-Contract-Based Digital Payment Chain System (DPCS) to protect subcontractors, and requiring pre-bid local adaptation training for foreign contractors. These recommendations aim to construct "embedded institutional resilience," transforming policy intent into executable governance mechanisms to ensure infrastructure investment genuinely serves Sarawak's inclusive and sustainable growth.

Keywords: Foreign construction firms; Local enterprise participation; Low-cost bidding; Industrial chain fragmentation; Dependency theory; Institutional capacity; Economic resilience

Online publication: October 10, 2025

1. Introduction

Sarawak, a focal point of regional development in East Malaysia, has pursued rapid economic growth through major infrastructure initiatives such as the Pan Borneo Expressway and the KUTS urban transit system. However, the influx of foreign investors—particularly Chinese construction companies—has presented significant challenges to the local economic structure. This paper investigates the effects of foreign participation in Sarawak's infrastructure sector, particularly on local industrial linkages, enterprise engagement, and the effectiveness of policy implementation. It further proposes constructive countermeasures grounded in both theoretical analysis and empirical evidence [1].

This study is guided by three core research questions:

(1) How does foreign-led infrastructure development constrain local industry participation?

(2) What factors hinder effective policy enforcement?

(3) How can Sarawak cultivate adaptive mechanisms to foster local economic resilience?

The findings of this study also provide broader implications for public investment strategies in other resource-rich regions across Southeast Asia.

2. Sarawak's infrastructure development policy context and implementation structure

Since 2016, Sarawak has implemented large-scale infrastructure projects, including the RM16 billion Pan Borneo Highway [2], RM4.5 billion Kuching Urban Transportation System (KUTS), and the Rural Transformation Programme (RTP) with annual funding exceeding RM1.5 billion. Under the *Post-COVID-19 Development Strategy 2030 (PCDS 2030)*, infrastructure investment is projected to grow over 8% annually, comprising more than 33.5% of the state's total budget. This strategy harnesses infrastructure development as a catalyst for industrial upgrading, leveraging embedded technological capabilities and institutional innovation to generate sustainable multiplier effects.

However, Sarawak's complex geography (e.g., dense rainforests, mountainous terrain) and extreme tropical climate (annual rainfall >4,000 mm) impose high technical and capital demands on infrastructure projects. Local firms face structural constraints including:

(1) Limited access to advanced technologies (e.g., AI-driven construction systems)

(2) Financing bottlenecks (higher loan rates vs. international players)

(3) Shortages of skilled labor (only 22% engineering graduates meet industry needs)

In contrast, foreign contractors—particularly Chinese firms—leverage superior resources, as shown in **Table 1**.

Table 1. Competitive edge: Chinese contractors vs. local firms

Competitive edge	Chinese contractors	Local firms
Capital capacity	Syndicated loans at <3% interest	Average bank rate 6.5%
Equipment	Autonomous machinery fleets	78% rely on leased equipment
Engineering expertise	150+ projects in tropical regions	Average 2 large-scale project experiences

These disparities position international players as dominant in public tenders, as evidenced by the KUTS Blue Line tender requirements, as shown in **Table 2**.

Table 2. Minimum scale requirements and supporting documentation for project types

Project type	Minimum scale requirement	Notes
ART or rail projects	Contract value ≥RM100 million	Provide copies of contracts and project verification documents
Urban infrastructure	Total length ≥5 km, or single structure (e.g., bridge) ≥100 meters	Include as-built drawings, handover certificates, etc.
Smart traffic systems	Experience covering ≥5 stations (e.g., dispatching, ticketing, surveillance)	Include system integration or software configuration details

Bidding companies must demonstrate sound financial stability, with the following indicators, as shown in **Table 3**.

Table 3. Financial and creditworthiness requirements

Requirement	Specific criteria
Audited financial reports	Audited statements for the last 3 consecutive years (including balance sheet, income statement, and cash flow statement)
Net assets	Net assets ≥RM50 million
Annual turnover	Annual revenue ≥RM100 million
Cash flow capacity	Provide proof of working capital or a bank credit line of at least RM 20 million
No debt risk	No significant outstanding debts, unresolved legal disputes, or breach of contract records in the reports

Resource: Tender document for Kuching Autonomous Rapid Transit (ART) Blue Line – Package 2

To mitigate foreign dominance and advance industrial upgrading, Sarawak mandated three bidding conditions:

(1) Foreign firms must establish joint ventures with local partners;

(2) Local participation must cover at least 40% of project value (including equity, subcontracting, and employment);

(3) Bid evaluation adopts multidimensional scoring (60% technical/ESG, 40% price).

However, inadequate enforcement capacity (e.g., only 12 auditors for 142 projects in 2023) and local contractors' technical limitations (only 15% are proficient in BIM [Building Information Modeling]) have undermined implementation. Consequently, the policy's intent to empower local industries remains unrealized, with foreign firms still winning 92% of mega-projects (>RM500 mil) in 2022–2024 [3].

3. Contradictions between foreign domination and local enterprise development

The growing dominance of foreign construction firms in Sarawak's infrastructure sector has created multiple tensions that hinder the development of local enterprises. Although intended to promote inclusive growth, current practices have often marginalized local actors and weakened the industrial spillover effect of public investment. This section outlines four key contradictions emerging from foreign-led infrastructure implementation [4].

3.1. Winning bids at low prices and marginalization of local enterprises

Chinese contractors consistently submit bids 15–22% below local cost benchmarks (CIDB 2023 Q3 Report), triggering unsustainable price competition. Although price constitutes only 40% of the evaluation criteria, foreign firms dominate the lowest-quartile bids in 83% of tenders (>RM500 mil).

Joint ventures (JVs) often operate as “shell partnerships”: Local entities are excluded from critical domains (e.g., BIM coordination, supply chain management), reducing their role to subcontractor-level participation (average profit share <15%). This violates Sarawak’s Genuine Partnership Guidelines 2022, requiring joint decision-making on ≥30% project value.

3.2. Weakening of the local industrial chain

Foreign contractors import 72% of materials and 65% equipment (e.g., tunnel boring machines from China), bypassing local suppliers. State audit data shows local participation averaged 21.3% in 2022–2023—half the 40% policy target—with only 12% of procurement value flowing to Sarawak-registered firms [5].

This import dependency stifles local industrial linkages: For every RM1 billion project, RM380 million potential local value-add is lost (World Bank 2023). This undercuts the intended industrial linkage effects and limits the growth potential of domestic supply chains [6].

3.3. Payment risks for downstream businesses

Systemic payment delays plague local subcontractors in foreign-led projects, driven by prime contractors’ low-bid strategies that necessitate downstream cost compression. At the Pan Borneo Highway Section 11 project, 87% of suppliers suffered delays exceeding 180 days, with 41% waiting over 12 months—triple the state average (World Bank Enterprise Survey 2023, Sarawak Module, N = 200) [7].

3.3.1. Structural roots lie in risk-shifting clauses:

“Pay-when-paid” (PWP) clauses allow primes to withhold payments until receiving owner funds, transferring liquidity risk to SMEs; “Pay-if-paid” (PIP) variants in 23% of contracts enable outright non-payment if the owner defaults [8].

3.3.2. Local firms lack bargaining power to reject these terms:

92% of subcontractors accepted PWP/PIP clauses under duress, fearing blacklisting from future bids (Sarawak Fair Contracting Report 2024).

3.4. Local social impacts

Labor inclusion failure: At the Kuching-Samarahan Expressway project, only 28% of skilled positions were held by locals vs. contracted 45%—a breach penalized by merely RM250,000 (<0.1% project value).

Accountability deficit: Of 17 safety incidents (2023), 14 were linked to design flaws by foreign engineers, yet liability was transferred to local subcontractors via “back-to-back” indemnity clauses (Sarawak OSHA Report Case #2023-047).

4. Challenges in project implementation: Climate, institutions, and execution

The rollout of foreign-led infrastructure projects in Sarawak has encountered a range of interlocking challenges that undermine their timely and cost-effective delivery [9,10]. These challenges span across three core domains:

(1) Environmental and geological constraints: Sarawak’s extreme rainfall patterns, peat-rich soils, and landslide-prone terrains require highly localized engineering solutions. Many foreign contractors lack adequate adaptation strategies for tropical climates and complex subsoil conditions, leading to frequent delays and structural issues.

(2) Institutional mismatches and regulatory complexity: The coexistence of Malaysian Standards (MS) and

legacy British Standards (BS), compounded by multi-level approval processes involving federal, state, and indigenous authorities, creates procedural ambiguity. Foreign firms often struggle with regulatory interpretation, licensing, and environmental approvals—resulting in legal disputes and prolonged bottlenecks.

(3) Executional limitations and resource gaps: Low-bid procurement strategies adopted by many foreign contractors often result in insufficient contingency planning and poor on-site resourcing. Inadequate technical protocols, workforce delays, and logistical inefficiencies further weaken execution capacity, particularly during monsoon seasons or on geotechnically unstable sites.

Collectively, these climate-driven, institutional, and operational barriers have contributed to widespread delays, cost overruns, and underperformance across major projects in Sarawak. Addressing them requires not only technical recalibration and better standard harmonization but also deeper alignment between foreign contractors and local institutional ecosystems.

4.1. Climate and geology adaptation

Sarawak's unique climatic and geological conditions pose serious challenges to infrastructure development, particularly for foreign contractors unfamiliar with the local terrain. The region experiences intense monsoonal rainfall and unpredictable subsoil conditions, which significantly increase engineering complexity, risk, and cost [11].

4.1.1. Climatic extremes and construction delays

Sarawak's monsoon season, typically spanning October to April, brings monthly rainfall exceeding 600 mm, among the highest in Southeast Asia. These torrential rains can quickly turn construction zones into inaccessible or unstable sites, especially in rainforest-covered areas where soil erosion and slope instability are common [12].

According to the World Bank (2024), in Sarawak's equatorial rainforest terrain, every single day of rain results in an average of 3.5 days of project delay, due to compounded effects such as:

(1) Limited access for heavy machinery,

(2) Prolonged drying and curing times for concrete works,

(3) Frequent site shutdowns for safety compliance.

This rainfall impact multiplier severely undermines project scheduling and demands sophisticated adaptive planning—something many foreign contractors fail to integrate into their bid-phase risk assessments.

4.1.2. Geological complexity and technical misjudgment

Sarawak's terrain is also characterized by its geotechnical heterogeneity, with approximately 35% of major infrastructure projects built on peatlands or landslide-prone zones. These conditions require hyper-localized geotechnical investigation, soil treatment strategies, and adaptive engineering design.

Yet many foreign firms, especially those unfamiliar with tropical geologies, underestimate subsurface risks. For example:

(1) On the Bintulu–Miri Highway, insufficient soil consolidation planning led to piling structures sinking 2.1 meters, primarily due to peat soil compression, a failure attributed to poor hydrogeological assessment.

(2) The Sarawak State Auditor-General Report (2024) highlighted similar issues in KUTS Phase 1, where slope failures and groundwater management errors caused delays totaling 9.3% beyond the planned schedule.

Across large-scale public projects in the state, average construction delays reached 14.7% in 2023, a figure significantly above the national benchmark. A substantial portion of these delays can be traced back to geological misjudgments and inadequate rain-adaptation protocols.

4.1.3. Root causes of underperformance

Key recurring deficiencies observed among foreign contractors include:

(1) Over-reliance on BS or GB soil classification methods without tropical soil calibration;

(2) Absence of real-time rain risk models in scheduling software;

(3) Generic slope stabilization designs that fail under local saturation and run-off conditions;

(4) Lack of contingency in budgeting for monsoon-induced rework or delayed mobilization.

4.2. Inadequate system and approval processes

Malaysia's construction sector is governed by a hybrid regulatory framework that integrates British Standards (BS), Malaysian Standards (MS), and Chinese Standards (GB). While this system is intended to align international best practices with national requirements, in practice, it has created systemic challenges, especially for foreign contractors unfamiliar with local regulatory nuances. These challenges include technical incompatibilities, bureaucratic ambiguity, and lengthy approval procedures, all of which contribute to delays, cost escalations, and credibility risks for non-local firms.

4.2.1. Technical standard conflicts

One of the most critical barriers to seamless project delivery lies in the conflicting technical requirements between BS, MS, and other national standards, such as China's GB system (**Table 4**). In particular, inconsistencies in geotechnical and soil testing protocols often force foreign contractors to redesign or revalidate key components mid-project, leading to schedule overruns and budgetary strain.

Table 4. Cross-jurisdictional technical conflicts

Conflict area	BS Standard	MS Standard	Chinese Standard (GB)	Impact
Slope safety	BS 8004:2015 – Foundations	MS EN 1997-1:2010 – Eurocode 7	GB 50007-2011 – Building Foundation Code	MS permits a 1.8× lower factor of safety compared to BS and GB, raising landslide risk and triggering redesigns or local authority rejections.
Peat soil testing	BS 1377-2:2022 – Soil Methods	MS 2801:2019 – Peat Soil Testing	GB/T 50123-2019 – Soil Test Methods	Saturation thresholds and shear strength metrics differ, resulting in incompatible test data and 3–6 month redesign delays.

These discrepancies not only undermine engineering consistency but can also erode contractor credibility, especially in public infrastructure and high-stakes tender environments.

4.2.2. Procedural bottlenecks

In addition to technical conflicts, foreign contractors must navigate Malaysia's multilayered and decentralized approval systems, which include federal ministries, state-level authorities, and indigenous land councils. This fragmented structure contributes to significant delays in environmental, land, and operational clearances.

(1) Environmental Impact Assessment (EIA) approval delays: According to data from CIDB's Project Dashboard 2023, foreign contractors face an average EIA approval period of 14 months, compared to 8 months for local contractors.

(2) Key contributing factors: NCR (Native Customary Rights) Land Certification: Projects located on or near NCR-designated lands must undergo mandatory tribal consultations, involving negotiations with multiple indigenous communities. This adds, on average, 4.7 months to the approval timeline (**Figure 1**).

(3) Language and legal misinterpretations: A CIDB arbitration case (2024-077) revealed that 38% of Chinese contractors misinterpreted the term "substantial completion" as referring to mechanical completion, resulting in premature handovers and a 22% project rework rate. This illustrates a critical need for multilingual contract templates and localized legal training.

4.2.3. Operational gridlock

Even after securing design and environmental approvals, foreign contractors frequently encounter downstream execution barriers, especially in areas such as equipment mobilization and skilled labor deployment. These issues are often caused by document mismatches, inconsistent certification protocols, and slow institutional processing.

(1) Equipment mobilization delays: Machinery sourced from abroad—often compliant with BS or GB standards—faces average customs delays of 17 days, due to non-alignment with Malaysia's MS-based certification. These delays disrupt project timelines and inflate idle equipment costs on-site.

(2) Professional licensing delays: Foreign engineers, particularly from China and the Republic of Korea, encounter average wait times of 68 days to receive MS-accredited licenses, in stark contrast to 14 days in neighboring Singapore. These licensing delays discourage expatriate professionals from long-term assignments, affecting project supervision and quality control.

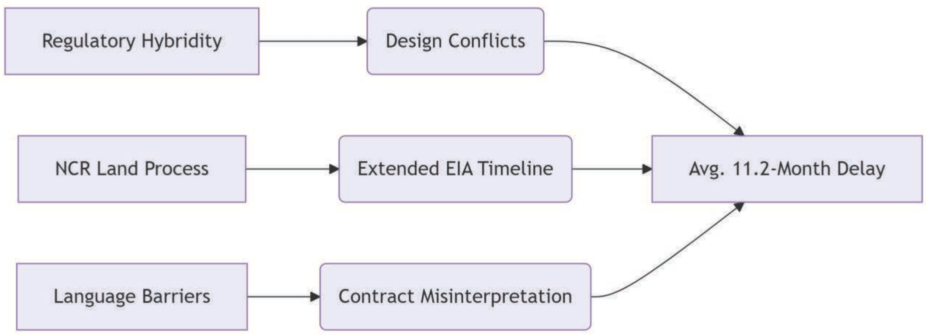


Figure 1. Systemic impact diagram

4.3. Insufficient resources for project execution

One of the most persistent challenges undermining timely and effective project delivery in Malaysia's construction sector is the issue of insufficient on-ground resources, particularly in large-scale infrastructure projects. This problem is notably acute among foreign contractors, whose bidding strategies and operational models often fail to account for local conditions and risk variables.

4.3.1. Bid-induced resource gaps

A key driver of resource insufficiency is the low-bid strategy commonly adopted by foreign firms in competitive tenders. While effective in securing contracts, this approach often results in compressed contingency budgets, leaving limited financial flexibility to respond to delays, design changes, or unforeseen site conditions (**Figure 2**).

According to CIDB Guideline 7A, a minimum contingency allocation of 8% is recommended for large-scale infrastructure projects in Malaysia. However, data from the CIDB Project Dashboard 2023 reveals that foreign bids often allocate less than 2.5%—a discrepancy that significantly increases project vulnerability to disruption. These tight margins frequently result in manpower shortages, delays in equipment deployment, and difficulties in engaging qualified subcontractors during peak demand periods.

4.3.2. Knowledge and protocol deficits

In addition to under-budgeting, foreign contractors often lack the technical protocols adapted to Malaysia's tropical monsoon climate. Approximately 79% of foreign firms operating in Malaysia do not possess monsoon-adapted construction protocols, such as:

(1) Specialized techniques for foundation stabilization in saturated clay soils;

(2) Real-time erosion and sediment control during prolonged rainfall;

(3) Adjusted scheduling models that account for seasonal weather volatility.

The absence of such context-sensitive know-how not only hinders operational continuity but also amplifies environmental and structural risks during project execution.

4.3.3. Delay divergence by contractor origin

These deficiencies are reflected in the project performance metrics reported by CIDB (**Table 5**). An analysis of 84 infrastructure projects exceeding RM500 million in value demonstrates.

Table 5. Clear divergences in outcomes based on contractor origin

Contractor type	Average delay (months)	Cost overrun (%)	Critical failure rate (%)
Chinese	7.3	22	71
Japanese	3.1	9	29
Local (Malaysian)	2.4	6	18

Source: Construction Industry Development Board (CIDB) Malaysia, Project Dashboard 2023, Kuala Lumpur.

Chinese firms, while securing a substantial portion of high-value contracts, exhibit the highest average delay (7.3 months) and critical failure rate (71%), often attributed to poor site adaptation, underestimation of local complexities, and limited engagement with local subcontractors. In contrast, Malaysian contractors outperform foreign counterparts across all indicators, with lower delays, tighter cost control, and fewer critical project failures—underscoring the value of contextual familiarity, stable local supply chains, and institutional learning.

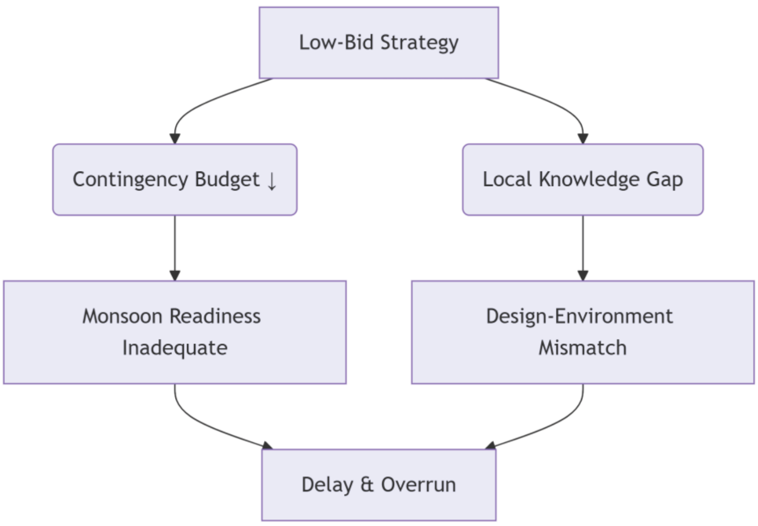


Figure 2. Causes and effects of low-bid strategy on project delay and cost overrun

5. Reframing structural dependency in infrastructure development

This chapter applies a revised dependency framework to examine Sarawak's overreliance on foreign firms in infrastructure projects. Traditional dependency theory highlights the risk of peripheral regions becoming structurally subservient to external capital. However, this study builds upon Evans' concept of disarticulated accumulation, where development is not merely dependent but increasingly decoupled from local productive systems.

In Sarawak's infrastructure sector, foreign firms dominate high-value projects but contribute minimally to knowledge transfer, local employment, and industrial upgrading. The result is a fragmented development pattern: while physical assets grow, local capacities remain underdeveloped.

5.1. Structural indicators of disarticulated accumulation

The dominance of foreign patent ownership illustrates a severe knowledge drain (**Table 6**). Despite growing investment in "green infrastructure," local firms are excluded from core technology development, which perpetuates dependence on external expertise.

Table 6. Ownership of green construction-related patents in Sarawak (2023)

Patent holder category	Share (%)
Foreign contractors	89%
Local contractors	6%
Universities & research bodies	5%

Source: WIPO Construction Tech Registry, 2023

This imbalance signals a classic feature of disarticulated accumulation: value extraction without reinvestment. Foreign firms capture the majority of economic surplus, while local supply chains remain shallow and undercapitalized (**Table 7**).

Table 7. Value flow in infrastructure projects (2023)

Financial flow	Amount (RM billion)
Foreign profit repatriation	6.8
Local contractor net earnings	2.7
Local material supplier net earnings	0.4

Source: Sarawak Treasury Report on Infrastructure Investment Returns, 2023

5.2. Institutional capacity deficits

Beyond structural dependency, Sarawak also suffers from institutional enforcement gaps, where policy intentions are routinely undermined by weak implementation mechanisms.

This study draws from Peters' theory of institutional capacity, which emphasizes two essential components:

(1) Adaptive governance: the state's ability to dynamically respond to implementation failures;

(2) Administrative capacity: the technical and organizational capability to enforce rules and monitor compliance.

To make these concepts operational within infrastructure governance, this study proposes the following conversion framework, as shown in **Table 8**.

Table 8. Translating institutional theory into infrastructure governance tools

Peters' concept	Operational mechanism	Southeast Asian example
Adaptive governance	Tiered penalty for localization shortfall (e.g., 0.2% contract deduction per 1% gap)	Vietnam's Expressway Project (Decree 10/2022)
Administrative capacity	AI-driven blockchain system to track compliance, fund flows, and technology transfer	Indonesia's Patimban Port Project (JICA, 2023)
Rule enforcement	Mandatory Local Participation Index (LPI) auditing & digital payment chain	Proposed in Sarawak context

These mechanisms transform Peters' theoretical dimensions into a three-part regulatory toolkit for Sarawak: Legislative anchors, Digital enforcement instruments, and Execution accountability.

5.3. Synthesis: Beyond dependency, toward embedded institutional resilience

Sarawak's infrastructure landscape does not reflect a lack of development activity, but rather a misalignment between growth and local empowerment. Projects are often executed by foreign-led consortia with minimal integration into the local ecosystem.

This section argues that breaking the dependency cycle requires more than revised procurement laws; it demands an institutional shift—from passive rule-setting to active performance governance. Embedding smart contracts, performance-based penalties, and localization verification systems into Sarawak's infrastructure delivery will be essential.

The next section explores how peer economies in Southeast Asia have implemented such institutional innovations, and what Sarawak can learn from their successes and failures.

6. International experience and comparative analysis

To address structural imbalances arising from foreign dominance in infrastructure, several Southeast Asian countries have pioneered policy mechanisms that balance external participation with domestic development goals. A common pattern across these efforts is the emergence of a "constraint–incentive–assessment" triadic framework, which seeks not only to localize project inputs but to institutionalize enforcement and accountability.

6.1. The Philippines: Local sourcing preference with incentives

In 2019, the Philippine government implemented a "60% local sourcing preference" policy for infrastructure projects exceeding USD 50 million. Under this approach, foreign contractors were encouraged—though not mandated—to procure at least 60% of inputs locally. Compliance with this benchmark triggered fiscal incentives, including VAT exemptions and accelerated customs clearance.

As a result, domestic building material suppliers' market share rose from 35% to 52%. However, weak oversight enabled several foreign firms to misreport procurement data, avoiding compliance without repercussion.

Lesson for Sarawak: Legal mandates are more enforceable than soft preferences. A price-based prioritization clause (e.g., "local offer ≤115% of foreign bid") could be codified in procurement law to ensure enforceability, paired with randomized audits to verify reporting.

6.2. Indonesia: Mandated technology transfer and blockchain monitoring

The Tanjung Priok Port Redevelopment Project, led by Chinese firms, introduced a mandatory technology transfer clause requiring that at least 20% of the local workforce receive formal technical training. A third-party auditing team, co-appointed by the government and a bilateral agency, tracked contractor compliance.

Outcomes: Local skilled labor participation rose from 12% to 30%. However, cost overruns and delayed deliverables persisted.

Separately, in the Patimban Port Project, Indonesia piloted AI-driven blockchain systems to track real-time local participation data. Combined with a training fund requirement (0.5% of contract value), this helped raise the share of certified local engineers from 18% to 37%.

Lesson for Sarawak: Institutional capacity is strengthened not only through rules, but through digital compliance mechanisms. AI + blockchain can provide tamper-proof monitoring of labor, fund flows, and localization efforts.

6.3. Vietnam: Enforcement via tiered penalty system

In Vietnam's Northern Expressway Project, foreign contractors were required to localize 40% of core components (e.g., bridges, tunnel segments). This compelled foreign and local firms to co-develop critical infrastructure elements, resulting in the emergence of three domestic tier-1 contractors.

What set Vietnam apart was its tiered penalty system:

(1) For every 1% shortfall in localization, 0.2% of contract value was deducted.

(2) Localization performance was tracked quarterly, verified by an inter-agency team.

Lesson for Sarawak: Adaptive enforcement can be embedded through contractual penalty schedules, aligning Peters' "adaptive governance" theory with tangible outcomes.

6.4. Synthesis: Toward a closed-loop localization model

Across these three cases, successful elements coalesce into a triadic strategy in **Table 9**.

Table 9. Comparative policy framework: ASEAN localization tools

Country	Constraint mechanism	Incentive tool	Assessment method
Philippines	60% sourcing preference (non-binding)	Tax exemptions	Self-reporting with weak auditing
Indonesia	Mandatory training + tech transfer	Training fund (0.5% contract value)	Blockchain monitoring + third-party audit
Vietnam	40% localization clause + penalties	Procurement scoring bonus	Tiered penalty (0.2%/1% shortfall)

Sources: World Bank (2022); JICA (2023); Vietnam MOC (2022)

6.5. Implications for Sarawak

These comparative insights offer clear implications:

(1) Replace quotas with enforceable preference systems

→ Codify price-based local sourcing rights in procurement law.

(2) Mandate tech transfer contributions

→ Require foreign contractors to deposit 0.8% of contract value into a Technology Transfer Fund, verified by public-private monitors.

(3) Adopt tiered penalties for non-compliance

→ Introduce a localization penalty clause modeled on Vietnam's Decree 10/2022.

(4) Deploy digital compliance tools

→ Invest in AI-enhanced blockchain systems for real-time tracking of labor, materials, and payment chains, modeled after Indonesia's Patimban Port.

These reforms would shift Sarawak's current infrastructure governance model from symbolic compliance toward embedded institutional enforcement.

7. Policy recommendations

Building on Sarawak's empirical findings and regional policy experiences from Southeast Asia, this chapter proposes a comprehensive set of actionable recommendations to enhance institutional resilience and realign foreign infrastructure investment with local development objectives. Each recommendation addresses a specific governance gap identified in previous chapters.

7.1. Reforming the bid evaluation and price review mechanism

To prevent "race-to-the-bottom" bidding and protect project quality, Sarawak should introduce a Low-Bid Risk Evaluation System (LRES) that flags submissions deviating ±20% from market-based cost curves. Bidders must submit a risk reserve justification, verified by third-party cost consultants (aligned with CIDB cost standards).

Recommended enhancements:

(1) Mandatory risk disclosure: Projects with abnormally low bids must provide cost-risk mitigation plans.

(2) Enhanced penalties: Firms engaging in unsustainable pricing should face escalating sanctions:

(a) First violation: Written warning

(b) Second violation: Temporary disqualification (1–3 years)

(c) Third violation: Blacklisting (aligned with RA 9184, Philippines)

(3) Reputation-based disclosure: Publish violators on public procurement portals to increase reputational cost.

7.2. Strengthening the Local Participation Index system

A Local Participation Index (LPI) should be used as a mandatory scoring dimension in all major infrastructure tenders (**Table 10**). The LPI should reflect actual economic embedding, not merely formal partnerships.

Table 10. LPI key components

Indicator	Weight (%)	Verification mechanism
Local equity share	30%	Joint signatory bank rights audit
Technology transfer	40%	Co-registered IP & training evidence
Local employment	30%	EPF & SOCSO-linked workforce database

Bidder score <60% on LPI = automatic disqualification from future tenders for 2 years.

Compliance architecture:

(1) Real-time monitoring: Via a digital dashboard accessible to authorities, contractors, and community observers.

(2) Cross-verification: Between statutory bodies and independent engineering consultants.

7.3. Establishing a digital fund disbursement and oversight system

To resolve chronic delays in subcontractor and supplier payments, Sarawak should introduce a Digital Payment Chain System (DPCS) based on milestone-based smart contracts and a State Treasury-controlled escrow mechanism.

Core features:

(1) Centralized treasury account: All public project funds flow through a controlled escrow account.

(2) Auto-triggered milestone payments: Disbursed directly to subcontractors based on verified completion.

(3) Overdue compensation clause: Payments delayed beyond 30 days to incur a 1.5% monthly penalty, modeled on Malaysia's "Contractor Payment Protection Act, Article 5."

7.4. Implementing a local adaptation training framework for foreign contractors

Foreign contractors should be required to undergo a certified pre-bid orientation program covering Sarawak's regulatory, environmental, and cultural operating context.

Mandatory curriculum:

(1) Tropical Civil Engineering Standards (80 hours)

(2) Indigenous Land & Rights Protocols (case-based learning)

(3) Occupational Health & Environmental Compliance (CIDB + EQA alignment)

Enforcement mechanism:

(1) Bidders failing to pass the course will have their technical evaluation score reduced by 30%.

(2) Courses managed jointly by CIDB Sarawak, state universities, and indigenous community boards.

7.5. Summary: Toward an embedded enforcement ecosystem

Together, these reforms embed verification, incentives, and consequences into Sarawak's infrastructure delivery system (**Table 11**). By moving beyond policy declarations toward enforcement-ready mechanisms, Sarawak can unlock the full multiplier potential of infrastructure investment while safeguarding its local economy.

Table 11. Closed-loop infrastructure governance framework for Sarawak

Reform area	Institutional tool	Enforcement mechanism
Bid evaluation	LRES + technical scoring	Market deviation thresholds + blacklisting
Local participation	LPI with hard indicators	Score threshold + contract-linked penalties
Fund flow transparency	Digital payment chain	Treasury escrow + auto penalties
Foreign contractor fit	Pre-bid training certification	Mandatory course + score deduction for failure

8. Conclusion: Toward infrastructure decoupling and institutional resilience

Sarawak's infrastructure development dilemma illustrates a deeper structural contradiction between the imperatives of global economic integration and the pursuit of inclusive, locally embedded growth. While foreign contractors have introduced capital, technology, and large-scale delivery capacity, their prolonged dominance has crowded out local firms, diluted industrial learning effects, and exposed gaps in Sarawak's institutional enforcement architecture.

Through the lens of Evans' disarticulated accumulation theory, this study identifies a critical risk: infrastructure-led growth that bypasses domestic capacity building and perpetuates value leakage and knowledge dependency. Simultaneously, Peters' framework of institutional capacity helps illuminate why well-intentioned localization policies in Sarawak often fail—not due to poor design, but due to fragile enforcement, limited feedback mechanisms, and reactive governance models.

To reverse this path, the study calls for a fundamental transition from policy symbolism to performance enforcement. Four institutional pathways emerge from the analysis (**Table 12**):

(1) Embedded verification: Through tools like the Local Participation Index (LPI), enforced with hard indicators (equity, patents, employment), verified by AI-assisted audit systems.

(2) Responsive penalty systems: Tiered consequence structures such as Vietnam's 0.2% deduction model, tied directly to localization shortfalls.

(3) Digital infrastructure governance: Smart-contract-based disbursement platforms, ensuring real-time, conditional fund flows and minimizing rent-seeking and payment delays.

(4) Knowledge localization: Mandated technology transfer funding, compulsory contractor training, and co-patenting provisions that convert passive procurement into capacity-building platforms.

These are not abstract principles—they are implementable policy levers, already piloted in the Philippines, Indonesia, and Vietnam, and shown to be adaptable under Sarawak's existing legal and administrative frameworks.

Table 12. "Infrastructure Decoupling" pathway to 2030

Target dimension	2023 baseline	2030 goal (PCDS)
Local value-added in foreign projects	28%	45%
Tier-1 local infrastructure contractors	4 firms	12 firms
Green tech patent localization	11%	35%

Source: PCDS 2030 Mid-Term Review; WIPO; Sarawak Treasury

These goals are attainable—but only through a restructured governance architecture, where policy, technology, and enforcement co-evolve.

8.1. Final reflection

Sarawak stands at a critical inflection point. The question is no longer whether infrastructure can drive growth, but what kind of growth, for whom, and under whose control. By embracing institutional resilience and embedding accountability, adaptability, and digital traceability into its infrastructure ecosystem, Sarawak can shift foreign investment from a vector of dependency into a vehicle of inclusive transformation.

Breaking the "dependent growth trap" requires not rejection of foreign involvement, but a recalibration of the terms—a governance reset where infrastructure becomes both a physical and institutional asset. Only then can Sarawak fulfill its 2030 vision: infrastructure not merely as expenditure, but as a sovereign pathway to industrial and commercial self-determination.

8.2. Others

Delays in municipal road projects, in particular, have led to severe traffic congestion. This creates additional social costs due to the time wasted by road users during traffic jams. These losses can be estimated based on congestion duration and user volume, potentially forming the basis for a separate research agenda.

Funding

(1) Research on the Impact of Navel Orange Industry Development on the Ecological Environment and Its Countermeasures (Project from Jiangxi Provincial Department of Science and Technology, 2012BBF60185, Second Principal Investigator: Jinqiao Ling)

(2) Research on the Reform of Cultural Foundational Courses in Vocational Colleges and the Cultivation of Students' Professional Quality (Provincial Social Science Project, JXJGYX-2011-32, Second Principal Investigator: Jinqiao Ling)

(3) Research on Promoting Green Ecological Creation in Ganzhou (Ganzhou Federation of Social Sciences

Circles, JXGZ-2010-09, Principal Investigator: Jinqiao Ling)

Disclosure statement

The authors declare no conflict of interest.

References

[1] Cardoso FH, Faletto E, 1979, Dependency and Development in Latin America, University of California Press, Berkeley, CA.

[2] Peters BG, 2015, Institutional Theory in Political Science: The New Institutionalism (4th ed.), Edward Elgar Publishing, Cheltenham, UK.

[3] Sarawak State Government, 2016, Sarawak Development Blueprint 2030, Planning Unit, Chief Minister's Department, Kuching.

[4] Sarawak Ministry of Economic Affairs, 2023, Audit Report on Local Participation in Infrastructure Projects (Report No. MEA/SWK/2023-05), State Government Press, Kuching.

[5] World Bank, 2022, Philippines Infrastructure Procurement Review: Local Sourcing and Fiscal Incentives, World Bank Group, Washington, DC.

[6] Japan International Cooperation Agency (JICA), 2023, Tanjung Priok Port Redevelopment Project: Compliance and Impact Assessment (Technical Report No. 2023-17), Japan International Cooperation Agency, Tokyo.

[7] Philippine Department of Finance (DOF), 2021, Enforcement Gaps in Infrastructure Local Sourcing Policy (White Paper Series).

[8] Vietnam Ministry of Construction (MOC), 2022, Northern Expressway Project: Localization and Contractor Development, Vietnam National Publishing House, Hanoi.

[9] SME Association Sarawak, 2024, Contractor Contracting Conditions and Fair Practice Report, SME Association Sarawak, Kuching.

[10] CIDB Malaysia, 2023, CIDB Project Dashboard and Guideline 7A, Construction Industry Development Board, Kuala Lumpur.

[11] World Intellectual Property Organization (WIPO), 2023, Construction Tech Patent Registry – Sarawak Chapter, WIPO, Geneva.

[12] Sarawak Treasury Department, 2023, Infrastructure Investment Returns Report, Sarawak Treasury, Kuching.

Journal of Architectural Research and Development, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Innovative Models and Practical Paths of Concrete Technical Management in Construction Engineering

Yafei Wu*

Shenzhen 518000, China

**Author to whom correspondence should be addressed.*

Abstract: This paper focuses on concrete technical management in construction engineering. It explains the core elements, including production mix ratio, analyzes problems of traditional models, presents innovative management models like BIM + GIS and their applications, and covers aspects such as job competence standards and prefabricated modular construction regulations, emphasizing the significance and development direction of innovative models.

Keywords: Concrete technical management; Innovative models; Construction engineering

Online publication: October 10, 2025

1. Introduction

Concrete technical management is of vital importance to the quality of construction engineering. Its core elements include production mix ratio management, construction process control, and quality monitoring and evaluation. In recent years, with the development of the construction industry, China has successively issued a series of relevant policies. For example, the *Opinions on Promoting Green Development in Urban and Rural Construction*, released in 2021, emphasized the importance of construction engineering quality and sustainable development. This has set higher requirements for concrete technical management. Traditional management models have many problems, such as inaccurate material batching, non-standard construction operations, and inefficient quality control. However, the application of innovative models, such as digital management platforms based on BIM + GIS and embedded sensor network systems, has brought new opportunities and challenges to concrete technical management. At the same time, these innovations also provide strong support for improving the quality and efficiency of construction projects.

2. Theoretical basis of concrete technical management

2.1. Core elements of concrete technical management

The core elements of concrete technical management include production mix ratio management, construction process control, and quality monitoring and evaluation. Production mix ratio management requires precise calculation of the proportions of each component based on the engineering requirements and the characteristics of the raw materials to ensure that the concrete performance meets the standards [1]. Construction process control covers various stages such as pouring, vibration, and curing, and it is essential to strictly follow the construction techniques and operational standards to ensure the quality and stability of the concrete structure. Quality monitoring and evaluation involve testing the strength of concrete specimens and conducting durability tests to identify potential issues in a timely manner and take measures to resolve them. These three elements are interrelated and mutually influential, forming the core of concrete technical management and providing an important guarantee for the quality of construction projects. Effective management of these elements can help reduce material waste, improve construction efficiency, and enhance the overall durability and safety of the structure.

2.2. Analysis of current industry management status and issues

Data from typical engineering quality accidents over the past five years indicate that traditional concrete technical management models have many problems. In terms of material waste rate, a significant amount of concrete material is wasted due to the lack of precise batching and usage plans [2]. The strength qualification rate is also not satisfactory. Improper control of the mix ratio and non-standard curing during construction lead to concrete strength failing to meet the required standards. The crack occurrence rate is also high, closely related to unstable raw material quality, unreasonable construction techniques, and inadequate post-construction curing. These problems not only affect the quality of the project but also increase costs and reduce the overall efficiency of construction projects. For example, improper estimation of the required concrete volume can result in excess material that cannot be reused effectively. Insufficient vibration during pouring can result in voids within the concrete, reducing its strength and durability. Thermal cracks can form due to rapid temperature changes during curing, especially in mass concrete structures. Addressing these challenges requires innovative approaches to concrete technical management that can improve precision, reduce waste, and enhance overall quality control.

3. Construction of intelligent innovation models

3.1. Full-lifecycle intelligent control system

A digital management platform based on BIM + GIS can be constructed to form a full-lifecycle intelligent control system by integrating functional modules such as material traceability, construction simulation, and risk warning. BIM provides a building information model that accurately presents the details of each stage of concrete construction [3]. GIS endows the system with spatial analysis capabilities to locate the sources of materials and construction sites. The material traceability module can trace the information of concrete raw materials to ensure quality. The construction simulation module leverages the visual advantages of BIM to simulate the construction process, identify potential issues in advance, and optimize the construction plan. The risk warning module combines data from both BIM and GIS to provide real-time monitoring and early warning of risks during construction, such as concrete cracking and insufficient strength. By integrating these modules into a full-lifecycle intelligent control system, it is possible to achieve a closed-loop management process that ensures the quality and safety of the concrete throughout its entire lifecycle. This system not only improves the precision and efficiency of concrete management but also enhances the overall sustainability of the construction project.

3.2. Application of Internet of Things data acquisition technology

The development of an embedded sensor network system and its application in concrete technical management in construction projects can achieve real-time monitoring of key parameters such as mixing temperature, slump, and curing environment. By accurately collecting data through sensors, timely feedback on the state of concrete at different stages can be provided [4]. At the same time, an adaptive adjustment mechanism is used to automatically adjust relevant parameters based on the collected data to ensure that the quality and performance of the concrete meet the engineering requirements. On this basis, a dynamic decision-making model is established to comprehensively consider various factors and optimize the production and construction processes of concrete. This innovative mode helps to enhance the scientific and precise nature of concrete technical management and provides a strong guarantee for the quality of construction projects. For example, sensors in the mixing plant can monitor the temperature and consistency of the mix, while sensors in the formwork can monitor the curing conditions and detect any potential issues such as excessive temperature gradients. The data collected by these sensors can be transmitted in real-time to a central monitoring system, where it can be analyzed to provide valuable insights into the concrete's performance.

4. Design of management practice pathways

4.1. Organizational structure optimization strategies

4.1.1. Multi-professional collaboration mechanism

To effectively manage concrete technology in construction projects, a multi-professional collaboration mechanism must be established. A triple-helix cooperation architecture involving civil engineers, material experts, and data scientists should be designed. Civil engineers provide concrete application requirements from a structural design perspective, material experts develop suitable materials based on these requirements, and data scientists use data analysis to optimize concrete mix ratios and other parameters. Additionally, a project-based knowledge-sharing cloud platform should be established to promote the exchange and sharing of knowledge among different professions. Through this platform, professionals from various fields can promptly access the information they need, such as material performance data, engineering design requirements, and data analysis results. This breaks down professional barriers, improves collaboration efficiency, and enhances the level of concrete technical management [5].

4.1.2. Job competency standard system

The job competency standard system for concrete technology management in construction engineering should cover multiple aspects. Firstly, in terms of BIM operation ability, relevant personnel are required to be proficient in the application of BIM software in concrete engineering, including model construction, collision detection, etc., in order to better simulate and optimize construction [6]. The ability to analyze data is also crucial, as it can effectively analyze data on concrete raw materials, mix proportions, and strength, providing a basis for quality control. Furthermore, the ability to respond to emergency plans is indispensable. Personnel need to be familiar with various problems that may occur during the concrete construction process, such as cracks and insufficient strength, and be able to quickly take effective emergency measures to ensure that the quality and progress of the project are not affected. At the same time, a comprehensive talent training program and certification standards should be developed to ensure that personnel in the position possess these comprehensive abilities.

4.2. Standardized operation process re-engineering

4.2.1. Prefabricated modular construction standards

It is crucial to establish precision control standards and error compensation schemes for component lifting and positioning in prefabricated construction specifications. The lifting accuracy requirements for different types of components, such as columns, beams, slabs, etc., should be clearly defined, and reasonable positioning accuracy standards should be determined based on their stress characteristics and connection methods [7]. At the same time, corresponding compensation plans should be formulated for possible errors to ensure accurate installation positions of components and guarantee structural safety.

In addition, developing technical specifications for modular interface processing is also crucial. The specifications should cover the form, size, tolerance, and fit of interfaces, clarify the connection methods and requirements between different modules, ensure the compatibility and reliability of interfaces, and improve the overall quality and construction efficiency of prefabricated buildings.

4.2.2. Special concrete construction guidelines

For self-compacting concrete, it is necessary to improve the database of pouring parameters. Data on pouring parameters, including pouring speed, height, and temperature, should be collected under different engineering environments and concrete mix ratios to provide accurate references for subsequent construction [8]. Additionally, in the construction of super-high-rise buildings using pump-fed concrete, verticality correction is crucial. A detailed correction process should be established, with precise measurement of allowable verticality deviation ranges before construction. During construction, high-precision measuring instruments should be used to monitor verticality in real-time, and any deviations should be promptly corrected by adjusting the angle and position of the pumping equipment to ensure that the concrete is accurately delivered to the designated location and to guarantee the construction quality of super-high-rise structures.

5. Empirical research and benefit analysis

5.1. Case of the Shanghai Center project

5.1.1. Application of C80 high-strength concrete

The application of C80 high-strength concrete in the Shanghai Center project involves comprehensive research on its performance. Through intelligent curing systems, the strength development curve is optimized to better meet the engineering expectations and provide reliable strength support for super-high-rise building structures [9]. Effective control of early-age shrinkage and deformation is also critical. In this project, precise monitoring and analysis of relevant data ensure that the shrinkage and deformation of the concrete during the early-age period are within a reasonable range, avoiding structural cracking and other issues caused by excessive shrinkage and deformation. This improves the durability and stability of the concrete structure and provides valuable practical experience and data support for the application of similar high-strength concretes in high-rise buildings in the future.

5.1.2. Economic benefit assessment

In the Shanghai Center project, the innovative model significantly reduces labor costs compared to traditional methods. By adopting advanced concrete technical management innovation models, unnecessary manual operation links are reduced, and work efficiency is improved, effectively controlling labor costs [10]. In terms of rework rate, the innovative model shows a significant advantage. Traditional methods may result in higher rework rates due to poor technical management, while the innovative model, with its precise control of concrete technology, greatly reduces the occurrence of rework, thereby minimizing the economic losses caused by rework. In terms of construction period reduction, the innovative model optimizes the construction process, avoiding delays caused by concrete technical issues, enabling the project to be completed ahead of schedule. This not only reduces indirect costs during the construction process but also allows the project to be put into use earlier to generate economic benefits.

5.2. Practice of the Hong Kong-Zhuhai-Macao Bridge project

5.2.1. Improvement of marine concrete durability

The Hong Kong-Zhuhai-Macao Bridge project has conducted in-depth practice in improving the durability of marine concrete. By comparing the monitoring data of chloride ion permeability coefficients, the effectiveness of the triple-protection system is verified. In the actual project, special concrete mix ratio designs are used, and high-performance admixtures and mineral admixtures are added to enhance the chloride ion permeability resistance of the concrete from a material perspective. At the same time, a protective coating is applied to the surface of the concrete structure to further prevent the ingress of chloride ions. Moreover, the construction process is optimized to ensure the density of the concrete, reducing porosity and thereby decreasing the channels for chloride ion permeation. Monitoring data shows that the chloride ion permeability coefficient is significantly reduced after the implementation of the triple-protection system, effectively demonstrating its ability to enhance the durability of marine concrete and providing a guarantee for the long-term safe use of the bridge.

5.2.2. Environmental benefit calculation

In the environmental benefit calculation of the Hong Kong-Zhuhai-Macao Bridge project, the improvement in green construction indicators such as waste recycling rate and carbon emission intensity is statistically analyzed. Through proper planning and the application of advanced technologies, waste generated during the bridge construction is effectively recycled and reused, increasing the waste recycling rate. At the same time, energy-saving and emission-reduction measures are taken in the production, transportation, and construction of materials, reducing carbon emission intensity. These improvements reflect the positive contributions of the Hong Kong-Zhuhai-Macao Bridge project to environmental protection and provide a reference for the green construction of subsequent large-scale construction projects, promoting the sustainable development of the construction industry.

5.3. Wuhan Yangtze River Shipping Center project

5.3.1. Temperature control scheme for mass concrete

In the temperature control scheme for mass concrete in the Wuhan Yangtze River Shipping Center project, distributed fiber-optic monitoring data is analyzed. This monitoring method can obtain key data such as the internal temperature changes of the concrete in real time. At the same time, based on these data, the crack-prevention effect of the intelligent water-cooling system is assessed. The intelligent water-cooling system plays an important role in temperature control. Reasonable water-cooling parameter settings and system operation can effectively reduce the internal temperature gradient of the concrete, decrease the generation of temperature stress, and thus minimize the possibility of crack formation. Analysis of the monitoring data shows that the system has achieved good crack-prevention effects in this project, ensuring the quality and stability of the mass concrete structure and providing useful references for temperature control and crack prevention in similar projects.

5.3.2. Technology innovation diffusion model

To deeply study the diffusion of technological innovation in the Wuhan Yangtze River Shipping Center project, it is crucial to construct a regression equation of the correlation between the technology adoption rate and project scale and enterprise qualifications. First, a large amount of data related to the adoption of concrete technology in the project should be collected, including the adoption situation at different construction stages, project scale, and enterprise qualification information. Then, using scientific statistical analysis methods, these data are processed and analyzed. Through regression analysis, the specific correlation between technology adoption rate and project scale and enterprise qualifications is determined. This not only helps to understand the diffusion law of concrete technology in the project but also provides references for the technical management of subsequent similar projects, better promoting the innovation and application of concrete technology in construction projects and improving the overall efficiency of the projects.

6. Conclusion

In construction projects, the innovative models of concrete technical management are of great significance. The new management models can effectively improve the quality of concrete, ensuring the stability and safety of the project, while also achieving cost savings and improving economic benefits. In terms of process innovation, it also has a positive driving effect. For better development, it is necessary to improve the industry standard system to make it more standardized and scientific, providing clear guidance for concrete technical management. With the advancement of technology, the application prospects of digital twin technology in the full-lifecycle management of concrete are broad. It can achieve precise simulation and monitoring of the entire process of concrete from production to use, identify problems in a timely manner, and optimize management, further improving the efficiency and quality of concrete technical management and promoting the sustainable development of the construction industry.

Disclosure statement

The author declares no conflict of interest.

References

[1] Zhang N, Konyalioglu AK, Duan H, et al., 2023, The Impact of Innovative Technologies in Construction Activities on Concrete Debris Recycling in China: A System Dynamics-Based Analysis. Environment, Development and Sustainability, 26(6): 14039–14064.

[2] Blismas N, Wakefield R, Hauser B, 2010, Concrete Prefabricated Housing Via Advances in Systems Technologies: Development of a Technology Roadmap. Engineering, Construction and Architectural Management, 17(1): 99–110.

[3] Ghaffar SH, Corker J, Fan M, 2018, Additive Manufacturing Technology and Its Implementation in Construction as an Eco-Innovative Solution. Automation in Construction, 93: 1–11.

[4] Sacks R, Pikas E, 2013, Building Information Modeling Education for Construction Engineering and Management. I: Industry Requirements, State of the Art, and Gap Analysis. Journal of Construction Engineering and Management, 139(11): 04013016.

[5] Zavadskas EK, Antucheviciene J, Vilutiene T, et al., 2017, Sustainable Decision-Making in Civil Engineering, Construction and Building Technology. Sustainability, 10(1): 14.

[6] Lloret E, Shahab AR, Linus M, et al., 2015, Complex Concrete Structures: Merging Existing Casting Techniques with Digital Fabrication. Computer-Aided Design, 60: 40–49.

[7] De Schutter G, Lesage K, Mechtcherine V, et al., 2018, Vision of 3D Printing with Concrete—Technical, Economic and Environmental Potentials. Cement and Concrete Research, 112: 25–36.

[8] Lehne J, Preston F, 2018, Making Concrete Change: Innovation in Low-Carbon Cement and Concrete. Chatham House Report, 2018: 13.

[9] Zhou M, Lu W, Song J, et al., 2018, Application of Ultra-High Performance Concrete in Bridge Engineering. Construction and Building Materials, 186: 1256–1267.

[10] Alexander M, Beushausen H, 2019, Durability, Service Life Prediction, and Modelling for Reinforced Concrete Structures–Review and Critique. Cement and Concrete Research, 122: 17–29.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Journal of Architectural Research and Development, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Architectural Design Technology Management: The Key Path to Improving Design Quality

Weihua Yuan*

Shenzhen 518000, China

**Author to whom correspondence should be addressed.*

Abstract: Architectural design technology management covers multiple aspects, including the formulation of technical standards, method selection, etc. It plays a key role in design quality, such as establishing a closed-loop management mechanism for the entire process and utilizing BIM collaborative platforms. It also introduces the application of techniques such as parametric design and the construction of quality prediction models. Simultaneously elaborating on the formulation of enterprise standards and other related content, this paper finally proposes an integrated solution while pointing out development bottlenecks and prospects.

Keywords: Architectural design; Technical management; Design quality

Online publication: October 10, 2025

1. Introduction

Architectural design technology management is crucial for improving the quality of architectural design. With the development of the construction industry, relevant policies are constantly improving, such as the *Opinions on Promoting Green Development of Urban and Rural Construction* released in 2021, which emphasizes the importance of building quality and sustainable development. Architectural design technology management covers various aspects such as the formulation and implementation of design technology standards, the selection and optimization of design technology methods, and has an impact on multiple fields such as building functional layout and structural selection. It drives the improvement of design quality through key links such as standardizing design processes, applying technical standards, and introducing new technologies. At the same time, BIM collaborative platform, parametric design technology, etc., play an important role in it. The establishment of a full process closed-loop management mechanism, comprehensive evaluation system, and quality performance assessment system also provides guarantees for improving design quality. However, it also faces some development bottlenecks, and digital twin technology may be able to break through in the future.

2. Theoretical framework of architectural design technology management

2.1. The core connotation of technical management

Architectural design technology management is a series of activities that systematically plan, organize, coordinate, and control various technical elements involved in the architectural design process [1]. Its connotation includes the formulation and implementation of design technical standards, ensuring that the design complies with relevant specifications and industry requirements. At the same time, it involves the selection and optimization of design techniques and methods to improve design efficiency and quality. In terms of scope, it covers multiple aspects such as functional layout, structural selection, material selection, and equipment configuration of buildings. It has a strategic positioning in quality control, by strictly controlling technical processes, preventing and reducing design defects, ensuring the safety, applicability, and durability of buildings, and thereby improving the overall quality of building design.

2.2. Analysis of quality-driven mechanism

Architectural design technology management plays a key driving role in design quality. Technical management covers multiple aspects, including the standardization of design processes, the application of technical standards, and the introduction and integration of new technologies. These aspects are interrelated and jointly affect the quality of design. For example, a standardized design process can ensure an effective connection between each link and avoid quality issues caused by poor communication or chaotic processes. The strict implementation of technical standards can ensure that the design meets basic quality requirements and provide a basic guarantee for high-quality design. At the same time, the reasonable introduction of new technologies and effective integration can stimulate innovative thinking, enhancing the competitiveness and quality level of design [2]. By deeply analyzing the correlation between these elements and their impact on design quality, a model of the role of technical management and design quality can be constructed, providing theoretical support for architectural design technical management.

3. Optimization of the design process and technical control

3.1. Full-cycle quality control system

Establishing a closed-loop management mechanism for the entire process of scheme design, construction drawing deepening, and technical disclosure is the key to improving the quality of architectural design. In the design phase, it is necessary to comprehensively consider various factors such as building function, aesthetics, and environment to ensure the scientific and rational nature of the design concept. In the process of deepening construction drawings, attention should be paid to details, relevant specifications and standards should be strictly followed, and detailed coordination and integration should be carried out for various disciplines such as structure, water, and electricity. The technical disclosure process should ensure that the construction team accurately understands the design intent and provides detailed explanations of key technical points and quality control requirements [3]. Through this closed-loop management of the entire process, design errors can be effectively avoided, design quality can be improved, and the smooth implementation of construction projects can be guaranteed.

3.2. Construction of collaborative design platform

The BIM collaborative platform plays an important role in the management of architectural design technology. In terms of professional collaboration, by creating a unified 3D information model, designers from various disciplines can carry out design work on the same platform, achieving real-time information sharing and interaction, and improving design efficiency and accuracy. For example, structural designers can obtain timely spatial layout information from architects and carry out reasonable structural design [4]. In terms of conflict detection, BIM platforms can automatically detect collision conflicts between different professions, such as collisions between pipelines and structural components. Designers can adjust the design in a timely manner based on the test results to avoid rework and resource waste during the construction phase, effectively improving the quality of the design.

4. Digital technology empowers innovative practices

4.1. Application of parametric design technology

4.1.1. Algorithm generation design optimization

The algorithm-generated design optimization in parametric design technology is of great significance in the field of architecture. Through algorithms, design schemes can be rapidly iterated and optimized. For example, genetic algorithms can simulate the process of biological evolution and optimize various aspects of building form, structure, etc., to achieve better performance goals, such as lighting, ventilation, etc. [5]. Meanwhile, algorithms based on physical rules can simulate mechanical principles and optimize the stability and safety of building structures. In practical applications, tools such as Grasshopper provide a convenient platform for algorithm-generated design optimization. Designers can combine design intent with optimization goals by writing algorithm scripts, quickly generate multiple design solutions, and select the optimal solution through comparative analysis, thereby improving the quality and innovation of architectural design.

4.1.2. Performance-oriented design validation

Digital technology plays a crucial role in performance-oriented design validation. Taking the integration of energy consumption simulation and structural calculation technology as an example, through parametric design technology, various building parameters can be input into relevant software for accurate energy consumption simulation and structural calculation. This can not only evaluate the performance of the building in the early stages of design, but also optimize the design scheme by continuously adjusting parameters to achieve better energy-saving and structural safety effects [6]. This integration method enables designers to consider the performance requirements of buildings more comprehensively, avoiding potential omissions and irrationalities in traditional design methods, thereby improving the quality and feasibility of architectural design and providing strong support for the sustainable development of buildings.

4.2. AI-assisted design decision-making

4.2.1. Prediction of machine learning quality

Building a building design quality prediction model based on historical data is a key aspect of machine learning quality prediction in AI-assisted design decision-making. By collecting a large amount of historical architectural design data, including design parameters, construction results, usage feedback, etc., machine learning algorithms are used to mine potential patterns and patterns in the data. These algorithms can analyze the impact of different design factors on the final quality and establish predictive models accordingly. This model can predict potential quality issues in new design projects based on input design scheme-related data. This helps the designer to adjust the design scheme in advance, avoid potential quality risks, improve the design quality and the success rate of the project, and provide strong support for the technical management of architectural design [7].

4.2.2. Development of an intelligent drawing review system

Image recognition technology plays an important role in the standardized verification of intelligent image review systems. Its implementation logic is based on the digital processing of architectural design drawings, converting drawing information into a computer-readable data form. Analyze these data through algorithms and compare them with preset standards. For example, precise identification and judgment of the dimensions, positional relationships, and annotation information of building components. This technology can quickly and accurately identify non-compliant areas, greatly improving the efficiency and quality of drawing review, reducing potential omissions and errors in manual drawing review, and providing strong technical support for quality control in architectural design [8].

5. The path of standardization system construction

5.1. Preparation of enterprise technical standards

5.1.1. Development of a standardized construction atlas

The preparation of enterprise technical standards should pay attention to scientificity and practicality. The scope and key indicators of the standards should be determined based on the actual needs of architectural design and industry development trends. During the preparation process, fully consider the characteristics and differences of different projects to ensure the universality and flexibility of the standards. At the same time, we should actively learn from international advanced standards and experiences, and enhance the internationalization level of enterprise technical standards. For the development of standardized construction drawings, it is necessary to systematically organize and classify them based on enterprise technical standards. The atlas should include common architectural construction forms and node practices, accompanied by detailed diagrams and explanations, for the convenience of designers to refer to and use. By utilizing digital technology, dynamic updates and maintenance of the atlas can be achieved to ensure its timeliness and accuracy. This not only helps to improve design efficiency but also enhances design quality, providing strong support for architectural design technology management [9].

5.1.2. Development of quality control checklist

Establishing a comprehensive design achievement inspection index system covering all specialties requires starting from multiple aspects, such as standardization system construction path, enterprise technical standard preparation, and quality control checklist formulation. In terms of the standardized system construction path, it is necessary to clarify the standards for each process to ensure the standardization and uniformity of the design process. The preparation of enterprise technical standards should be based on industry standards and practical experience, covering key elements such as design methods and material selection, to provide technical guidance for design. The development of a quality control checklist should focus on various aspects of the design results, including the accuracy of drawings, compliance with specifications, etc., and provide detailed inspection points to ensure that the design quality can be effectively controlled, thereby improving the overall quality of architectural design [10].

5.2. Talent echelon training mechanism

5.2.1. Capability model for technical leaders

It is crucial to establish a comprehensive evaluation system that includes professional skills and management abilities in architectural design technology management. For the construction path of the standardization system, it is necessary to clarify the standards of each process to ensure that the design complies with the specifications. In terms of talent development mechanisms, emphasis should be placed on hierarchical training, with corresponding growth paths for beginners to senior designers. For the ability model of technical leaders, they should have solid professional knowledge, including architectural design principles, various specifications, etc. At the same time, one should have excellent management skills, be able to arrange teamwork reasonably, and control project progress. Innovation ability is also required to respond to constantly changing market demands and design concepts. In addition, communication and coordination skills are also indispensable. It is necessary to be able to effectively communicate with all parties to ensure the smooth progress of the project.

5.2.2. Development of continuing education curriculum

In the path of standardization system construction, it is necessary to closely integrate the development of talent development mechanisms and continuing education courses with the forefront of the industry. For the field of BIM application, courses covering BIM software basic operations, collaborative design processes, and BIM application throughout the project lifecycle should be developed. Enable designers to master BIM technology from beginner to proficient, and improve design efficiency and quality. In terms of green building, course modules such as green building concepts, evaluation standards, energy-saving design strategies, and renewable energy utilization are set up. By combining theory with case studies, students can gain a deeper understanding of the key points of green building design. At the same time, the curriculum should focus on practical operations and simulation projects, cultivate students' ability to solve practical problems, ensure that they can apply the knowledge they have learned to actual design projects, and improve the overall quality of architectural design.

5.3. Quality performance evaluation system

5.3.1. Design of multidimensional evaluation indicators

Establish a three-dimensional assessment model for quality outcomes, technological innovation, and team collaboration. The dimensions of quality outcomes cover indicators such as design compliance with specifications, accuracy and completeness of drawings, and timely project delivery, ensuring that design outcomes meet high-quality standards. The dimension of technological innovation focuses on the application of new technologies, innovative design methods, and the ability to solve complex problems, motivating designers to continuously explore new technologies to enhance their design competitiveness. The team collaboration dimension assesses internal communication efficiency, cross-departmental collaboration effectiveness, knowledge sharing level, etc., to promote the efficient operation of the design team. By comprehensively considering these three dimensions, a comprehensive and objective quality performance evaluation system is formed to provide strong guarantees for improving the quality of architectural design.

5.3.2. Construction of the reward and punishment linkage mechanism

Establishing a quality performance evaluation system and a reward and punishment linkage mechanism requires comprehensive consideration of multiple factors. For performance evaluation, quantitative indicators should be clearly defined, such as the innovation, feasibility, and compliance with standards of the design scheme, while setting reasonable weights. The salary system should be closely linked to performance evaluation results, with high compensation rewards given to outstanding performers to motivate employees to improve design quality. In terms of professional title evaluation, quality performance is taken as an important reference, and employees with outstanding performance are given priority consideration in professional title promotion. For the linkage of rewards and punishments, in addition to salary incentives, reward measures may include honorary titles, promotion opportunities, etc. Punishment measures are targeted at those who fail to meet quality standards, such as salary deductions, restrictions on project participation, and delayed professional title evaluations. Through this linkage mechanism, the quality of architectural design is effectively improved.

6. Conclusion

Architectural design technology management is the key to improving design quality. Through a systematic review of the four major paths of process reengineering, technological innovation, standard construction, and talent cultivation, an integrated solution has been developed. Process reengineering optimizes the design process to improve efficiency; technological innovation drives the updating of design methods; standard construction ensures the standardization of design; talent cultivation provides human resources support for high-quality design. However, there are currently bottlenecks in the development of technology management in areas such as data governance and intelligent decision-making. Looking ahead to the future, digital twin technology has broad application prospects in architectural design quality management and is expected to break through existing bottlenecks, further improve the quality of architectural design, and provide strong guarantees for the sustainable development of the construction industry.

Disclosure statement

The author declares no conflict of interest.

References

[1] Durmus U, Turkcu HC, Gunaydin HM, et al., 2010, In Quest of Total Quality Management Principles in Architectural Design Services: Evidence from Turkey. Gestao & Tecnologia de Projetos, 5(10): 4237.

[2] Choi J, Lee S, Kim I, 2020, Development of Quality Control Requirements for Improving the Quality of Architectural Design Based on BIM. Applied Sciences, 10(20): 7074.

[3] Arayici Y, Coates P, Koskela L, et al., 2011, Technology Adoption in the BIM Implementation for Lean Architectural Practice. Automation in Construction, 20(2): 189–195.

[4] Armstrong G, Allwinkle S, 2017, Architectural Technology: The Technology of Architecture. Back to the Future: The Next 50 Years, 2017: 803–812.

[5] Asefi M, 2010, Design Management Model for Transformable Architectural Structure, Symposium of the International Association for Shell and Spatial Structures (50th, 2009, Valencia), Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures: Proceedings. Editorial Universitat Politecnica de Valencia.

[6] Gunhan S, 2011, Analyzing Business Management and Technology Characteristics of Small and Medium-Sized Architectural Design Firms in Turkey. African Journal of Business Management, 5(22): 9007.

[7] Nikseresht M, Mozaffar F, Saleh Sedghpour B, et al., 2019, Principles of Architectural Management with a Focus on Design Management Education. Journal of Architectural Thought, 3(6): 44–58.

[8] Shen W, Hao Q, Mak H, et al., 2010, Systems Integration and Collaboration in Architecture, Engineering, Construction, and Facilities Management: A Review. Advanced Engineering Informatics, 24(2): 196–207.

[9] Akadiri PO, Chinyio EA, Olomolaiye PO, 2012, Design of a Sustainable Building: A Conceptual Framework for Implementing Sustainability in the Building Sector. Buildings, 2(2): 126–152.

[10] Tay YWD, Panda B, Paul SC, et al., 2017, 3D Printing Trends in Building and Construction Industry: A Review. Virtual and Physical Prototyping, 12(3): 261–276.

Journal of Architectural Research and Development, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Real-Time Monitoring and Intelligent Analysis Platform for Carbon Emission in Smart Power Plants

Jie Gao, Tiejun Lin, Zhannan Ma

Guoteng Shanxi Hequ Power Generation Co., Ltd., Xinzhou 036500, Shanxi, China

Abstract: As global climate change intensifies, the power industry—a major source of carbon emissions—plays a pivotal role in achieving carbon peaking and neutrality goals through its low-carbon transition. Traditional power plants' carbon management systems can no longer meet the demands of high-precision, real-time monitoring. Smart power plants now offer innovative solutions for carbon emission tracking and intelligent analysis by integrating IoT, big data, and AI technologies. Current research predominantly focuses on optimizing individual processes, lacking systematic exploration of comprehensive dynamic monitoring and intelligent decision-making across the entire workflow. To address this gap, we propose a smart carbon emission monitoring and analysis platform for power plants that integrates IoT sensing, multimodal data analytics, and AI-driven decision-making. The platform establishes a multi-source sensor network to collect emissions data throughout the fuel combustion, auxiliary equipment operation, and waste treatment processes. Combining carbon emission factor analysis with machine learning models enables real-time emission calculations and utilizes long short-term memory networks to predict future emission trends.

Keywords: Smart power plant; Real-time carbon emission monitoring; Intelligent analysis platform; Internet of Things perception

Online publication: October 10, 2025

1. Introduction

With the increasingly severe global climate change, carbon emission management has become a core issue for countries to achieve the Sustainable Development Goals. As one of the main sources of carbon emissions, the low-carbon transformation of the power industry plays a decisive role in achieving the goals of carbon peaking and carbon neutrality. In the context of carbon neutrality, the extensive carbon emission management model of traditional power plants has become inadequate for meeting the demands of high-precision and dynamic monitoring. As a crucial direction in intelligent control of power engineering, smart power plants integrate technologies such as the Internet of Things (IoT), big data, and artificial intelligence, providing a new technical pathway for real-time monitoring and intelligent analysis of carbon emissions. Existing studies focus on the optimization of a single link or the construction of static models, and lack of systematic exploration of dynamic monitoring and intelligent decision-making of the whole process. As a result, problems such as lagging carbon emission data collection and a single analysis dimension are still prevalent [1].

2. Correlation theory

2.1. Carbon emission monitoring theory

Carbon emission monitoring theory is the core foundation of smart power plant carbon emission real-time monitoring and intelligent analysis platform construction. Its core is to achieve accurate collection, processing, and analysis of carbon emission data through scientific monitoring methods and advanced technical means. The basic principle of carbon emission monitoring is based on the calculation of carbon emission factors in the energy consumption process, combined with real-time data collection technology, to build a multi-dimensional monitoring system. As a key area of carbon emission, the low-carbon development of the power industry needs systematic monitoring from three key links: power generation side, power grid side, and electricity consumption side. For example, the power generation side needs to calculate carbon emissions through fuel consumption, power generation efficiency, and other parameters; while the grid side needs to pay attention to the loss and indirect carbon emissions in the transmission and distribution process; while the monitoring of the electricity side needs to combine the terminal load changes and user behavior characteristics to form a complete monitoring chain.

2.2. Smart power plant theory

Smart power plant is an intelligent energy management system built on modern information technology, automatic control technology, and big data analysis capability. Its core is to realize dynamic optimization and precise regulation of the power generation process through an integrated platform. By real-time collection of equipment operation data, environmental parameters, and energy consumption information, combined with a prediction model and intelligent algorithm, the system forms a closed-loop management architecture covering the whole production chain. Its core features are manifested in three dimensions: digital perception, networked transmission, and intelligent decision-making. At the device level, sensor networks are deployed to achieve comprehensive physical space perception. Industrial Internet technology is utilized to construct a neural network for data interaction. Ultimately, through digital twin and bionic system architectures, the power generation process is virtualized and dynamically optimized.

The deep integration of smart power plants and carbon emission monitoring is essential to incorporate carbon emission indicators into the production optimization objective function through technical means. For example, in the optimization of generator set operation strategy, the output of distributed energy can be coordinated through two layers of game theory. The inner layer manages demand side response through a price elasticity coefficient model, and the outer layer establishes a multi-energy collaborative optimization framework based on renewable energy uncertainty analysis, so as to minimize carbon emissions while ensuring power supply reliability.

3. Platform architecture design

3.1. Data acquisition and transmission module design

In the platform architecture design, the data acquisition and transmission module serves as the foundational support layer of the system. Its design objectives are to achieve efficient collection, real-time transmission, and quality assurance for multi-source heterogeneous carbon emission-related data. The data acquisition phase adopts a distributed sensing architecture, deploying high-precision sensor networks and industrial equipment interfaces to establish a monitoring system that covers the entire production process of power plants. In the combustion system, temperature, pressure, flow sensors, and CEMS (continuous emission monitoring system) are deployed to collect core parameters such as fuel consumption and flue gas composition concentration in real time. Key equipment such as steam turbine and boiler is equipped with vibration and displacement monitoring devices, and the operation status data of the equipment is obtained through the SCADA system interface. In the flue gas treatment process, in addition to the conventional pollutant monitoring, carbon isotope analyzers are added to realize online identification of fuel types and provide a data basis for carbon emission source analysis. All sensors are manufactured to industrial protection standards, support 4-20mA, RS-485, and other standard communication protocols, and are equipped with an edge computing gateway for local data aggregation.

The unified data parsing middleware is developed in the protocol adaptation layer to support the standardized conversion of various industrial protocols such as Modbus, OPC UA, and Profibus, and build a service-oriented API interface to realize seamless docking with the superior system [2,3]. In view of the timing characteristics of data flow, the timestamp alignment and order guarantee algorithm is adopted to ensure that the synchronization error of multi-source data is controlled within 50 ms.

3.2. Data analysis and processing module design

As the core technical component of the platform, this module is responsible for the analysis, modeling, and intelligent analysis of carbon emission data. Its design focuses on real-time, high precision, and scalability. In the data preprocessing stage, the system first cleans and standardizes the collected raw data, removes invalid data through a missing value interpolation algorithm and an outlier detection model (such as an isolated forest algorithm), and then uses a multi-dimensional normalization method to unify the dimensions of heterogeneous parameters such as temperature, pressure, and fuel consumption (**Table 1**) [4]. The feature engineering module constructs the time series features through sliding window technology and extracts the physical correlation between key variables combined with domain knowledge to form a feature matrix containing historical emission intensity, equipment load rate, meteorological conditions, and other dimensions, laying a foundation for subsequent modeling.

Table 1. Data preprocessing record table (data_preprocessing_log)

Field name	Type	Restrain	Description note
preprocess_id	BIGINT AUTO_PK	PRIMARY	Pre-treatment batch ID
raw_data_id_range	VARCHAR(50)	NOT NULL	Original data ID range (e.g., 100001-100500)
missing_rate	DECIMAL(5,2)	NOT NULL	Original data missing rate (%)
outlier_count	INT	NOT NULL	Number of anomalies (detected by isolated forest algorithm)
normalization_type	ENUM	NOT NULL	Normalization methods (MinMax/Z-Score/Log, etc.)
process_duration_ms	INT		Preprocessing time (ms)
timestamp	TIMESTAMP(3)	NOT NULL	Processing completion timestamp

4. Experimental and result analysis

4.1. Experimental method and step

This study verifies and evaluates the functions and performance of the smart power plant carbon emission real-time monitoring and intelligent analysis platform through a systematic experimental process. The experimental design adopts a modular architecture, consisting of four phases: hardware deployment, system integration, data acquisition, and analysis validation. The hardware deployment utilizes a hierarchical architecture, featuring front-end installations of industrial-grade IoT sensor networks. These include the CEMS, fuel flow meters, and unit status collectors. Sensor data undergoes real-time preprocessing through 5G-MEC edge computing nodes before being transmitted to the cloud. The server cluster adopts a hybrid cloud architecture, with core computing modules deployed in private clouds to ensure data security. Data analysis services achieve high-concurrency processing through elastic scaling on public clouds. The experimental environment configuration complies with IEC 61499 industrial communication standards, maintaining network latency below 200 ms. Data transmission employs a dual-protocol redundancy mechanism using both MQTT 3.1.1 and OPC UA protocols [5].

The system integration phase focuses on verifying inter-module collaboration capabilities. The data acquisition layer utilizes Python-developed drivers to integrate multi-source heterogeneous devices, establishing sensor data dictionaries and standardized conversion protocols. This ensures compatibility for critical parameters, including SO_2, NO_x, CO_2 concentrations, and fuel consumption metrics. The data processing layer uses Apache Kafka to build a real-time data flow pipeline and combines Flink to realize sliding time window calculation. A 10-second window period is set for emission rate calculation. The analysis layer is deployed with a TensorFlow-based LSTM-GRU hybrid neural network model to predict carbon emission trends, and a random forest algorithm is integrated to identify abnormal emissions.

4.2. Experimental results and analysis

Based on the actual operation data of a smart power plant, this experiment builds a carbon emission monitoring platform including multi-source sensor input, a real-time data processing module, and an intelligent analysis algorithm. This paper compares the performance of three methods in carbon emission monitoring: the traditional fixed coefficient method, the improved random forest algorithm, and the deep learning LSTM model. The experimental data were sourced from the 2022 operational records of a coal-fired power plant, encompassing 12 real-time parameters, including boiler load, fuel consumption, and flue gas composition, comprising 1.2 million valid samples. Through cross-validation and rolling window testing, we conducted a systematic evaluation of the monitoring accuracy, response time, and anomaly detection capabilities of various methodologies.

In the real-time index test, the single calculation response time of the fixed coefficient method is stable at 23 ms, the average delay of the random forest algorithm is 48 ms, and the LSTM model reaches 85 ms with GPU acceleration. Although the computing overhead of the deep learning model is high, the response time can be compressed to 62 ms through lightweight processing of the model (such as the introduction of knowledge distillation technology), which meets the real-time requirements of 500 ms for the power plant SCADA system. Experimental data show that the LSTM model can still maintain a real-time processing rate of more than 95% at the data throughput of 3000 points/second [6–10].

5. Conclusion

The smart power plant carbon emission real-time monitoring and intelligent analysis platform developed in this study has achieved remarkable results in both technical implementation and engineering applications. By integrating multi-source heterogeneous data acquisition systems, dynamic carbon emission accounting models, and intelligent decision support modules, the platform enables high-precision dynamic tracking and forward-looking analysis of carbon emissions throughout the entire power generation process. The research results show that the sensor network and edge computing architecture based on the Internet of Things can effectively improve the real-time performance and reliability of data collection, which lays a foundation for dynamic accounting of carbon emissions. The machine learning driven emission factor correction model performs well in the pilot of coal-fired units, and its prediction error is 18.7% lower than the traditional static accounting method, which significantly improves the accuracy of carbon emission data [10]. The multi-dimensional visual interface and abnormal emission early warning system developed by the platform have successfully reduced the response time of operation and maintenance personnel to minutes, effectively preventing the risk of sudden carbon emission exceeding the standard caused by equipment failure or process deviation.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Liu K, Yang X, Tai W, et al., 2022, Research on Carbon Emission Characteristics of Coal-Fired Power Units Based on Real-Time Monitoring. Thermal Power Generation, 51(10): 47–53.

[2] Liu S, 2024, Research on Low-Carbon Optimization Strategies for Virtual Power Plants Considering Demand Response and Multi-Energy Coupling Operations, dissertation, Shanxi University.

[3] Li J, Chang R, Sun S, et al., 2023, Application of Carbon Balance-Based Intelligent Emission Monitoring System in Thermal Power Plants. Coal Quality Technology, 38(1): 72–78.

[4] Kun L, Liu M, 2025, Application of Blockchain Technology in Carbon Emission Mechanism Design for Power Plants. Integrated Circuits Applications, 42(03): 202–203.

[5] Ding Z, Yang G, Sun E, et al., 2025, Research on Precise Energy Saving and Carbon Reduction Optimization in Power Plants Based on Intelligent Energy Management System. Modern Engineering Science and Technology, 4(04): 149–152.

[6] Yu D, Sun Q, Liu H, 2024, Study on Multi-Time-Scale Optimization Scheduling of Virtual Power Plants in Carbon Flow Computing. Journal of Nanchang University (Science Edition), 48(06): 604–611 + 620.

[7] Yao S, Liu Z, Lu Z, et al., 2024, Research Progress on Carbon Emission Measurement in Coal-Fired Power Plants Empowered by Soft Measurement Technology. Clean Coal Technology, 30(08): 18–31.

[8] Zhang N, Jia J, Li B, et al., 2024, Study on the Optimization of Operation Strategies for Electric-Gas Coupling Virtual Power Plants Considering Carbon Trading. Measurement and Instrumentation, 61(08): 20–28.

[9] Yu D, Wang X, Sun Q, et al., 2024, Multi-Objective Multi-Time-Scale Optimization Scheduling Based on VPP Carbon Flow Calculation. Smart Power, 52(01): 30–38.

[10] Fang B, 2023, Research and Application of Carbon Emission Accounting Technology System for Coal-Fired Power Plants. Energy and Energy Conservation, 2023(09): 94–97.

Integrated Services Platform of International Scientific Cooperation

Innoscience Research (Malaysia), which is global market oriented, was founded in 2016.Innoscience Research focuses on services based on scientific research. By cooperating with universities and scientific institutes all over the world, it performs medical researches to benefit human beings and promotes the interdisciplinary and international exchanges among researchers.

Innoscience Research covers biology, chemistry, physics and many other disciplines. It mainly focuses on the improvement of human health. It aims to promote the cooperation, exploration and exchange among researchers from different countries. By establishing platforms, Innoscience integrates the demands from different fields to realize the combination of clinical research and basic research and to accelerate and deepen the international scientific cooperation.

Cooperation Mode

BIO-BYWORD
SCIENTIFIC PUBLISHING PTY LTD

OUR JOURNALS

The *Journal of Architectural Research and Development* is an international peer-reviewed and open access journal which is devoted to establish a bridge between theory and practice in the fields of architectural and design research, urban planning and built environment research.

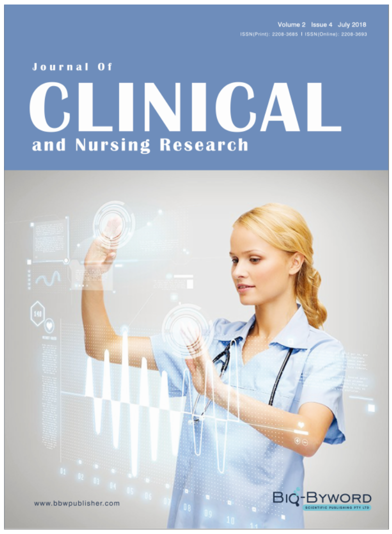
Topics covered but not limited to:

- Architectural design
- Architectural technology, including new technologies and energy saving technologies
- Architectural practice
- Urban planning
- Impacts of architecture on environment

Journal of Clinical and Nursing Research (JCNR) is an international, peer reviewed and open access journal that seeks to promote the development and exchange of knowledge which is directly relevant to all clinical and nursing research and practice. Articles which explore the meaning, prevention, treatment, outcome and impact of a high standard clinical and nursing practice and discipline are encouraged to be submitted as original article, review, case report, short communication and letters.

Topics covered by not limited to:

- Development of clinical and nursing research, evaluation, evidence-based practice and scientific enquiry
- Patients and family experiences of health care
- Clinical and nursing research to enhance patient safety and reduce harm to patients
- Ethics
- Clinical and Nursing history
- Medicine



Journal of Electronic Research and Application is an international, peer-reviewed and open access journal which publishes original articles, reviews, short communications, case studies and letters in the field of electronic research and application.

Topics covered but not limited to:

- Automation
- Circuit Analysis and Application
- Electric and Electronic Measurement Systems
- Electrical Engineering
- Electronic Materials
- Electronics and Communications Engineering
- Power Systems and Power Electronics
- Signal Processing
- Telecommunications Engineering
- Wireless and Mobile Communication