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The Practice of Biophilic Design in Indoor Space: Taking the Office as an Example

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Abstract: Biophilic design significantly enhances the ecological efficiency and humanistic value of office spaces by integrating natural elements with artificial environments. Studies show that this design can reduce building energy consumption by 15–20%, while increasing employee productivity by 12–18%. Key technical challenges include maintaining micro-ecological balance and cross-system collaborative control, and the lack of cost-benefit quantification tools hinders market promotion. As green building evaluation systems improve, intelligent environmental regulation technologies and standardized assessment methods will become key focuses for future development, providing scientific support for sustainable office environment construction.

Keywords: Biophilic design; Office space; Sustainable architecture

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1. Introduction

With the acceleration of urbanization, modern office environments are increasingly isolated from nature, leading to issues such as decreased employee mental health and reduced work efficiency. Biophilic Design, which integrates natural elements into architectural spaces to re-establish the connection between humans and nature, has become an important approach to improving indoor environmental quality [1]. The "14th Five-Year Plan for Building Energy Efficiency and Green Building Development" issued by the Ministry of Housing and Urban-Rural Development in 2023 clearly promotes the concept of green and low-carbon design, encourages the use of ecological building materials and natural ventilation and lighting technologies, and provides policy support for the application of Biophilic Design in office spaces [2]. Research has shown that introducing plants, natural light, and organic materials into offices can significantly enhance employee satisfaction and reduce carbon emissions, aligning with the sustainable development needs under the "dual carbon" goals [3]. Against this backdrop, exploring the practical strategies and benefits of Biophilic Design in office spaces is of great practical significance for promoting the construction of healthy buildings and low-carbon cities.

2. Theoretical basis of nature-friendly design

2.1. The connotation of nature-friendly design

The theoretical foundation of Biophilic Design stems from the "Biophilia Hypothesis" proposed by Wilson (1984) [4], which posits that humans have an innate emotional and physiological dependence on nature. This hypothesis reveals the deep influence of natural elements on human cognition, emotions, and behavioral patterns from an evolutionary psychology perspective [5]. Based on this, Biophilic Design reconstructs the connection between artificial environments and ecosystems by systematically integrating natural elements. This article is framed around "14 Biophilic Design Patterns" [6], with design elements divided into three major categories and fourteen subcategories: direct natural elements, such as physical interventions like vegetation, water bodies, and natural light; indirect natural metaphors, including abstract expressions like natural material textures, organic forms, and ecological colors; and spatial experience creation, which emphasizes simulating natural settings through techniques such as spatial sequence, visual transparency, and microclimate regulation (**Table 1**). These three categories of elements together constitute a multi-layered design intervention system, aiming to compensate for the lack of natural experience in modern architectural environments.

Table 1. Browning's 14 biophilic design patterns (Table source: redrawn by the author)

Design patterns	Design elements
Nature in space	1. Visual connections; 2. Non-visual connections; 3. Irregular sensory stimuli; 4. Heat and air flow; 5. Water body design; 6. Dynamic and diffused light; 7. Natural systems
Nature analogies	1. Natural forms; 2. Natural materials; 3. Complexity and order
Naturalistic space	1. Outlook; 2. Sanctuary; 3. Mystery; 4. Riskiness

2.2. The value of nature-friendly design in office environments

The application of nature-friendly design in office environments yields comprehensive benefits across multiple dimensions. From a psychological perspective, the introduction of natural elements can significantly reduce cortisol levels and alleviate cognitive fatigue through the Attention Restoration Theory (ART) mechanism, thereby enhancing creative output efficiency by 15–20% [7]. Physiologically, indoor plant communities can absorb more than 30% of volatile organic compounds (VOCs), and when combined with passive humidity regulation systems, they can maintain a relative humidity range of 40–60% that is optimal for human comfort [8]. Organizational behavior research shows that office spaces with nature-friendly design increase employee retention rates by 12–18%, and companies that have obtained LEED or WELL certifications exhibit significant advantages in attracting talent [9]. These benefits collectively constitute the intrinsic motivation for modern enterprises to adopt nature-friendly design, making it a core strategy for enhancing the quality of office spaces.

3. Key strategies for nature-friendly design in offices

3.1. Direct introduction of natural elements

The nature-friendly design of office spaces primarily achieves direct integration of natural elements through two approaches. In terms of plant configuration, vertical greening systems utilize modular planting units to facilitate space-efficient utilization. Ecological walls, combined with automatic irrigation technology, can establish a stable indoor micro-ecosystem. Meanwhile, mobile potted plant systems provide a flexible means of space division. Natural light optimization strategies emphasize passive design in architecture, with light wells using light-guiding technology to introduce natural light into deeper spaces.

High-transmittance glass partitions ensure visual connectivity while reducing the need for artificial lighting.

Intelligent dynamic shading systems automatically adjust based on the sun's angle, achieving optimal lighting and thermal comfort balance throughout the year. These technical measures collectively create an office environment with biophilic characteristics. Furthermore, the introduction of water features, such as indoor water curtain walls or small fountain systems, not only enhances the aesthetic appeal of the space but also regulates air humidity, enhancing the ecological perception of the environment. The use of natural materials, such as wood, stone, and bamboo, strengthens the connection between humans and nature both visually and tactually.

Natural ventilation strategies, utilizing operable window sashes, wind towers, or atrium designs, introduce fresh air and improve indoor air quality. These diverse technical measures collectively create an office environment with biophilic characteristics, effectively enhancing user comfort and work efficiency (**Table 2**).

Table 2. Direct incorporation of natural elements (Table source: drawn by the author)

Key strategies for biophilic office design	Implementation methods	Design elements
Direct integration of natural elements	Vertical greening	Visual connections;
	Portable potted plants	Visual connections;
	Light wells	Dynamic and diffused light;
	Smart shading systems	Dynamic and diffused light;
	Water walls, Mini fountains	Visual connections; Water body design;
	Natural materials	Natural materials; Visual connections;
	Wind towers, Atriums	Non-visual connections; Heat and air flow;

3.2. Indirect expression of natural imagery

In spaces where direct incorporation of natural elements is not feasible, meticulous design of colors and textures can still evoke natural associations in users. The application of earthy tones follows environmental psychology principles, creating a sense of stability with low-saturation colors such as warm grays, terracotta, and moss green. The color temperature is controlled within the range of 3000–4000K to simulate natural lighting effects.

The composition of organic forms draws on fractal geometry theory, breaking the mechanical feel of artificial environments through design languages such as asymmetric curves and irregular interfaces. In terms of material selection, recycled wood with natural textures and mineral coatings not only meet visual needs but also enhance the user's natural experience through tactile feedback [10].

Additionally, creating a soundscape is also an important approach. By introducing natural sound effects (such as flowing water and bird songs) or using materials with natural sound sensations (such as bamboo wind chimes), the ecological atmosphere of the space can be effectively enhanced.

Odor design is equally important. Utilizing natural plant essential oils or wood aromas can evoke memories of natural environments such as forests and grasslands, enhancing the natural affinity of the space. Simulating light and shadow effects can also enhance natural perception, such as using dynamic light projection technology to simulate the effect of sunlight passing through leaves, or using translucent materials to create a soft natural light sensation. These diverse indirect expression methods, while maintaining the functionality of modern office spaces, successfully incorporate ecological aesthetic values, further enhancing users' comfort and psychological pleasure (**Table 3**).

Table 3. Direct introduction of natural elements (Table source: drawn by the author)

Key strategies for biophilic office design	Implementation methods	Design elements
Indirect expression of natural elements	Earth tones	Visual connections;
	Natural textures	Visual connections;
	Color temperature of simulated Natural light	Visual connections;
	Organic forms	Natural forms;
	Wind chimes with natural Sound effects	Dynamic and diffused light;
	Natural plant essential oils	Irregular sensory stimuli
	Aromatic wood	Irregular sensory stimuli
	Soft translucent materials	Dynamic and diffused light

4. Case study on the practice of nature-friendly design in offices

4.1. Case studies of co-working spaces abroad

4.1.1. Case background: Second Home co-working space in London

Second Home, located in the Spitalfields area of East London, spans two floors and covers approximately 6,000 square meters. It stands as a typical example of biophilic office space design in recent years (**Figure 1**).

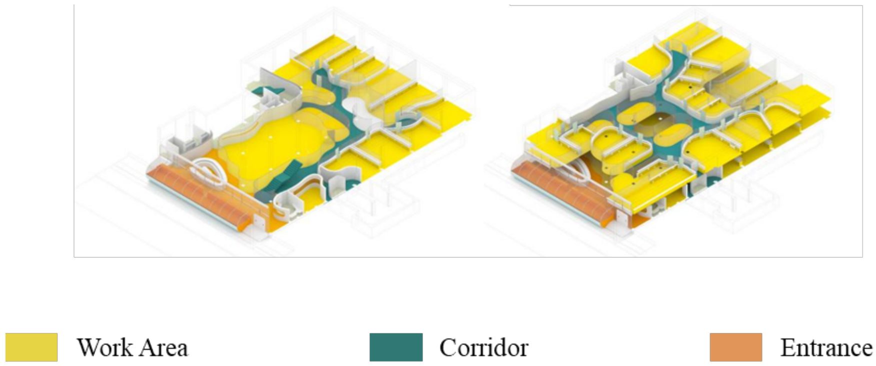

Figure 1. Ground and second floor plans (Image source: www.Archaily.com).

Its core objective lies in enhancing users' physical and mental health, as well as social interaction efficiency, through the deep integration of architecture and the natural environment. Distinct from traditional enclosed and mechanized office spaces, Second Home leverages natural light, abundant vegetation, and an organically flowing spatial layout to create an open and ecologically rich workplace. By introducing and integrating natural elements, this project not only fulfills individuals' physiological health needs but also enhances psychological pleasure and cognitive focus. Furthermore, Second Home has further expanded the connotation of biophilic design in terms of spatial organization and atmosphere shaping, transforming the office space into a "second home" that integrates ecology, creativity, and social interaction. Thus, this case exemplifies the trend of contemporary office environments shifting from functionality to humanism and sustainability.

4.1.2. Design highlights: deep integration of natural elements, dynamic optimization of environmental rhythms, and comprehensive enhancement of multi-sensory experiences

Firstly, in terms of the introduction of natural elements, the project extensively arranges green vegetation both indoors and outdoors (**Figure 2A**), giving the office environment the characteristics of an "urban oasis" or "indoor forest”. This large-scale vegetation not only provides natural scenery at the visual level, but also plays a positive role at the physiological and psychological levels, helping to reduce stress levels, enhance emotional states, and increase happiness [11].

Secondly, the project has undergone refined design in terms of light environment and spatial rhythm. Through large-area floor-to-ceiling glass, skylights, and translucent partitions (**Figure 2B**), the indoor space is able to maximize the introduction of natural light, allowing users to perceive changes in day and night and seasons during daily office work. This infiltration of dynamic light and shadow not only improves the comfort of the space but also helps regulate the human body’s biological clock, enhancing attention and productivity [12].

Furthermore, Second Home fully embodies naturalness and organicness in its spatial form and material selection (**Figures 2A and 2B**). The design abandons the straight and rigid layout typical of traditional office settings, opting instead for a curved and flowing spatial arrangement, coupled with organic materials such as natural wood and glass, creating a soft and warm spatial texture. This design not only enhances sensory comfort but also echoes the principle of “natural form and texture” emphasized in biophilic design [13].

Figure 2. The interior real scene photos. A. Integration of indoor and outdoor vegetation creating an “urban oasis” office environment; B. Use of natural lighting through floor-to-ceiling glass and skylights to enhance spatial rhythm and comfort. (Data source: www.Archaily.com).

4.2. Case of domestic enterprise headquarters

4.2.1. Case background: The headquarters of a real estate company

The project is located in the Economic and Technological Development Zone in the north of Langfang City, Hebei Province, on the north side of Xiangyun Road and the west side of Yuquan Road. The aboveground building area is 17,420.71 square meters, divided into three main office buildings: B, C, and D (with a standard floor area of 2,100 square meters for buildings B + C). The building height is ≤ 48 meters, serving as the headquarters building for the real estate company. The internal functions include customer service/intelligent capability operation center, lifestyle experience center, and a core focus on the company’s advanced intelligent and ecological office concept. The project innovatively combines nature-friendly design with employee behavior and scenario-based creation, hoping to provide new ideas for corporate headquarters office spaces (**Figure 3 and Figure 4**).

Figure 3. Architectural rendering (Image source: Drawn by the author).

Figure 4. Standard floor plan of buildings B and C (Image source: Drawn by the author).

4.2.2. Design highlights: Disassembly and reference of natural elements, creation of scenes imitating natural elements

Firstly, the project fully utilizes the direct introduction and indirect expression of natural elements, breaking them down into four dimensions (**Figure 5**): vertical greenery (using broad-leaved plants such as turtle-back bamboo that are easy to grow in the north) can effectively reduce the sound and visual interference from dynamic spaces to static spaces; the use of natural-looking office carpets helps reduce employees' work pressure and enhance comfort; mobile flower beds can be used to flexibly divide spaces and be called upon as needed; desktop greenery can choose plants such as Pothos that are easy to maintain, increasing the green content of the space and enhancing the comfort of the office environment.

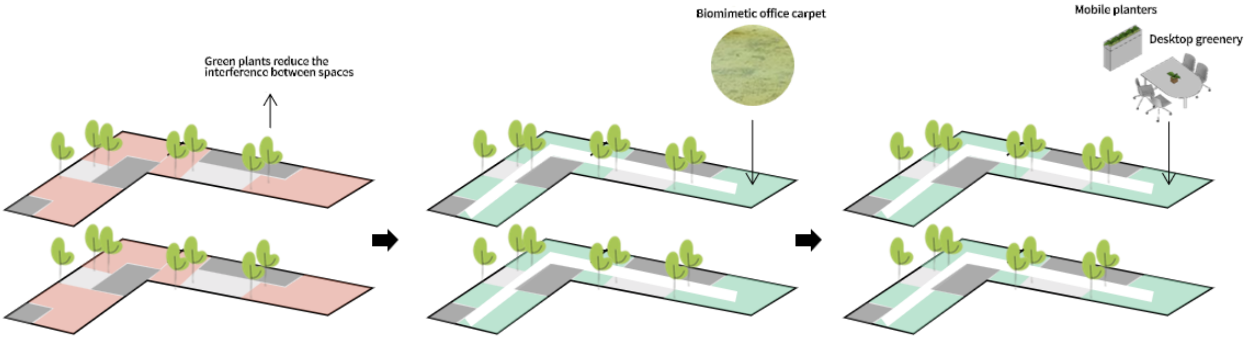

Figure 5. Incorporation of natural elements in the standard floor (Image source: Drawn by the author).

Secondly, the design utilizes natural wood-grain panels as the primary design element for the walls, combined with earth-toned paints for the ceiling and floor, as well as terrazzo, to simulate a natural indoor space. Furthermore, it incorporates linen carpets and locally green imitation grass carpets to distinguish different spatial attributes, complemented by organically shaped office furniture, creating various office scenarios that are conducive to employees' better value creation and work efficiency improvement (**Figure 6**).

Figure 6. Biophilic design in the standard floor office (Image source: Drawn by the author).

5. Challenges and optimization paths in the implementation of nature-friendly design

5.1. Technical challenge

5.1.1. Plant maintenance and indoor microecological balance

The sustainable operation of indoor plant systems faces multiple technical bottlenecks. Shade-loving plants have reduced photosynthetic efficiency in low-light environments, necessitating the use of artificial light compensation systems, which leads to increased energy consumption. The air circulation in enclosed spaces is limited, and plant transpiration often causes humidity to exceed the human comfort range. The imbalance of microbial communities is particularly prominent, and the concentration of mold spores in soil substrates may exceed standards. Existing solutions include developing new soilless cultivation media, using nano-coatings to inhibit the proliferation of pathogenic bacteria, and introducing intelligent environmental linkage systems. However, these technologies still have drawbacks such as high cost or insufficient stability, which restrict their large-scale application [14].

5.1.2. Collaborative control of natural lighting and artificial lighting

The design of building lighting interface faces the contradiction between sunlight radiation and visual comfort, and glare is prone to occur when the visible light transmittance (VLT) of the curtain wall exceeds 40%. The existing lighting control systems mostly use single factor adjustment of illumination, which is difficult to adapt to the lighting environment requirements of different work scenarios [15]. The new light environment management system achieves dynamic matching of natural lighting and LED supplementary lighting through a distributed illuminance sensor network and a working face illuminance demand model. However, the system has technical defects such as response delay (about 2–3 seconds) and abrupt regional transitions, and the high-precision sensor array increases the initial cost by 25–30%, which restricts the popularization of technology [16].

5.2. Coordinated control of natural lighting and artificial lighting

5.2.1. Economic challenges

The initial investment in nature-friendly design is 20–35% higher than that of traditional solutions, primarily due to the procurement of ecological materials (such as a 40% premium for FSC certified wood) and the deployment of intelligent systems [17]. The comprehensive cost of a vertical greening system reaches 3,000–5,000 yuan per square meter, and the payback period is usually over 5 years [18]. However, a full life cycle assessment shows that through reduced energy consumption (saving 15–25% annually) and improved employee efficiency (equivalent to 3–5% of annual labor costs), the investment payback period can be shortened to 3–4 years [19]. The current market lacks standardized assessment tools, making it difficult for owners to quantify potential benefits when making decisions, which hinders project financing. Establishing a comprehensive cost-benefit analysis model has become crucial for promoting the implementation of this technology.

5.2.2. Supply chain constraints of low-carbon materials

The current low-carbon building materials market faces severe structural contradictions between supply and demand. The production capacity of recycled building materials that meet EPD certification can only meet 15% of the market demand, resulting in a 60–90 days extension of the delivery cycle [20]. The problem of regional supply imbalance is prominent, and the transportation of low-carbon concrete prefabricated parts from the western region to the eastern coastal region actually increases the carbon footprint. The material certification system is highly fragmented, and the varying requirements for recycled material content in standards such as LEED and BREEAM make it difficult for manufacturing enterprises to achieve large-scale production, severely restricting the standardized promotion of nature-friendly design.

5.3. Optimization of design methodology

5.3.1. Quantitative assessment tools: Such as the nature-friendly indicators in the WELL building standard

The current evaluation system still has significant limitations in the quantitative evaluation of pro natural design. Although the WELL v2 standard establishes the concept of "natural systems" (Feature X05), its seven scoring indicators only cover 30% of biologically friendly environmental elements. Especially for the evaluation of spatial sequences and natural rhythms, there is a lack of objective parameters, mainly relying on subjective scores from experts. The emerging digital assessment tools attempt to establish a mathematical model of the correlation between alpha wave activity and natural elements through EEG monitoring and eye tracking technology, but the sample size is insufficient, resulting in low reliability and validity. Developing an intelligent evaluation platform that integrates physiological feedback and building parameters has become a key breakthrough direction for improving the scientificity of design.

5.3.2. Interdisciplinary collaboration: The Integration of architecture, environmental psychology, and IoT technology

The deepening of pro nature design urgently requires the construction of interdisciplinary collaboration frameworks. The architectural spatial form parameters (such as window to ground ratio and line of sight transparency) need to be quantitatively correlated with the stress threshold model (cortisol level < 15 **μg**/dL) used in environmental psychology research. The IoT sensor network can collect 12 environmental data in real-time, including CO_2 concentration (maintaining < 800 ppm) and light intensity (300–500 lux), but there are protocol incompatibility issues in multi-source information fusion. Digital twin technology provides a new path for interdisciplinary collaboration, integrating biometric data and building performance simulation through BIM platforms. However, the current efficiency of data exchange among various disciplines is insufficient. Establishing a unified data standard and collaborative design platform is the key to breaking through disciplinary barriers.

6. Conclusion

The application of nature friendly design in office spaces has evolved from a simple aesthetic pursuit to a systematic engineering that integrates environmental performance and humanistic care. Practice has shown that the intervention of natural elements in science can increase work efficiency by 12–18% and reduce building energy consumption by 20–30% [21]. The current technological bottleneck mainly focuses on the precision of microenvironment control and cross system collaboration, while the standardization of cost-benefit analysis will directly affect market acceptance. With the inclusion of biodiversity indicators in the scoring system of the “Green Building Evaluation Standards” (GB/T50378-2023), it is necessary to focus on breakthroughs in dynamic environmental optimization algorithms supported by digital twin technology in the future. The development of this field is not only related to the improvement of building performance, but also an important practice for reconstructing the symbiotic relationship between humans, buildings, and nature.

Disclosure statement

The author declares no conflict of interest.

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Study on Problems and Countermeasures in the Construction of Warping Dam Projects in the Loess Plateau Area

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Abstract: In recent years, to better address soil erosion, the Loess Plateau area has seen a surge in the construction of warping dam projects. Warping dams have strong functions in soil and water conservation as well as warping for farmland creation, serving as a key support for ecological restoration and economic development in the Loess Plateau area in the new era. However, in light of practical conditions, there are many problems in their construction process, which have affected their actual operation quality. In this regard, while expounding on the value and significance of warping dam project construction in the Loess Plateau area, this paper discusses the existing problems and effective countermeasures, aiming to provide some references for relevant personnel.

Keywords: Loess plateau; Warping dam project; Value and significance; Existing problems; Effective countermeasures

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1. Introduction

The Loess Plateau spans multiple provinces and autonomous regions in China, covering an area of 640,000 square kilometers. Due to natural characteristics such as thick loess layers, low vegetation coverage, and concentrated precipitation, it has become one of the regions with the most severe soil erosion in the world. Relevant data show that the annual soil erosion volume in the Loess Plateau is about 1.6 billion tons. This not only affects the local soil fertility and leads to land degradation but also directly causes sedimentation in the lower reaches of the Yellow River, posing hidden dangers such as floods and waterlogging disasters, which directly impact local social security and economic development. Warping dam projects, which began in the 1950s, integrate functions such as soil and water conservation, flood prevention and disaster reduction, and warping for farmland creation, and have gradually become an important "lifeline" for ecological management in the Loess Plateau [1]. At present, although warping dam projects are constantly being constructed and innovated, there are still problems such as unscientific planning and design and uneven construction quality, which directly affect the ecological environment protection and development of the Loess Plateau area [2]. In this regard, it is imperative and timely to actively explore the countermeasure paths for the construction of warping dam projects in the Loess Plateau area in the new era.

2. The value and significance of warping dam project construction in the loess plateau area

2.1. Ecological value: Consolidating the barrier for regional soil and water conservation and ecological restoration

For a long time, the Loess Plateau area has been facing severe soil erosion. Warping dam projects themselves have the functions of "blocking, storing, and silting", which are of great significance for soil and water conservation in the Loess Plateau [3]. From the perspective of sediment interception, a single warping dam project can intercept 2,000 to 5,000 tons of sediment annually, which can effectively alleviate the problem of sedimentation in the lower reaches of the Yellow River [4,5]. From the perspective of water storage, the project can convert surface runoff into water resources, which can effectively improve the local water source conditions and promote the hydrological cycle. In addition, the project can promote the improvement of the local microclimate. For example, it can use functions such as water storage of the dam body to form a small wetland ecological environment, promote the growth of local herbs, shrubs and other plants, and improve the local ecological environment [4].

2.2. Economic value: Promoting sustainable agricultural development and rural economic growth

Affected by factors such as poor soil and uneven precipitation, agricultural production in the Loess Plateau area lacks stability. The advancement of warping dam projects can effectively improve this situation. On the one hand, it can increase soil fertility through "blocking, storing, and silting", which effectively promotes the sustainable development of the local agricultural economy. On the other hand, compared with other lands, the dam land created by the project is rich in humus, which can effectively increase crop yields and lay a solid foundation for local food security. In addition, the construction and development of the project have also brought new opportunities for the development of local characteristic agriculture. For example, in the process of warping dam project construction in areas such as Yulin, Shaanxi, industries such as jujube and apple planting have been vigorously developed, which has effectively increased the income level of local farmers and injected new impetus into the development of the local rural economy [6].

2.3. Social value: Supporting rural revitalization and coordinated regional development

The construction of warping dam projects not only increases soil fertility and improves the yield of local food crops, but also promotes the "leveling" transformation of cultivated land, laying a solid foundation for the development of agricultural mechanization. Through the application of agricultural machinery, the efficiency of local agricultural production has been significantly improved [7]. At the same time, the project can also conserve local water sources, which can effectively solve the problem of domestic water use for local farmers. In addition, under the background of the project construction, industries such as rural tourism and rural e-commerce in the Loess Plateau area are developing vigorously, which also promotes the continuous upgrading of the agricultural industry and provides an important driving force for the implementation of the rural revitalization strategy and coordinated regional development.

3. Problems in the construction of warping dam projects in the loess plateau area

3.1. Planning and design level: lack of systematicness, scientificity, and poor adaptability

Scientific engineering planning and design are important foundations for ensuring the quality of warping dam projects. However, current warping dam projects in the Loess Plateau have problems such as insufficient systematicness, scientificity, and adaptability in planning and design, which affect the project quality and function performance. For example, in some river basin areas, the local river basin hydrological conditions are not fully considered during the construction of warping dams, and the distance design between dam bodies is unreasonable. This directly increases the local flood risk [8]. At the same time, the dam body coverage is insufficient in some areas. The existence of such "blind spots" poses great challenges to the overall soil and water conservation work. In addition, some warping dam designs adopt a "one-size-fits-all" approach, and the parameter design is not combined with local actual conditions. This leads to insufficient adaptability of the project and affects its actual function performance.

3.2. Project construction level: Uneven construction quality and ununified construction standards

At present, construction quality issues are prominent in the construction of warping dam projects in the Loess Plateau. On the one hand, construction units have problems such as simple equipment and unreasonable construction processes, resulting in substandard quality of warping dams. On the other hand, some construction units do not do a good job in controlling the quality of raw materials, such as using low-quality raw materials. This directly affects the quality of warping dams. In addition, the problem of ununified construction standards is also widespread. There are certain differences in relevant construction standards among different provinces, autonomous regions, cities, and counties. For example, the dam height standards in some areas are inconsistent with those in other areas. This situation not only affects the actual quality of warping dams but also brings certain difficulties to subsequent project acceptance and maintenance management [9].

3.3. Operation and management level: Imperfect management and protection mechanisms, and lagging post-maintenance

High-quality operation and management are the key to ensuring the effective operation of warping dam projects. However, current warping dam projects in the Loess Plateau generally have the problem of "emphasizing construction while neglecting management". For instance, some areas do not attach importance to the subsequent operation and management after the completion of warping dams, nor do they establish special departments for supervision and maintenance. This causes some warping dams to suffer from severe sedimentation within 3 to 5 years after completion, affecting the performance of their soil and water conservation functions [10]. Secondly, there are also problems in post-maintenance. For example, there is a lack of sufficient fund planning, the channels for social participation in maintenance and management are not fully utilized, and the enthusiasm of the masses to participate in management is insufficient. These factors all affect the effective operation of warping dams.

3.4. Monitoring and early warning level: Imperfect monitoring system and weak risk prevention and control capabilities

Currently, the layout of warping dam monitoring stations in the Loess Plateau is not reasonable. They are mainly concentrated around some key river basins or large-scale warping dams, failing to achieve full coverage. This leads to inadequate monitoring during the subsequent operation of the dams. In addition, the risk response system for warping dams is imperfect in some areas. On the one hand, monitoring personnel still use manual inspection methods to collect and analyze data, which has obvious shortcomings such as poor timeliness and long cycles. This affects the actual risk prevention and control capabilities. On the other hand, due to the lack of scientifically designed emergency plans, the risk prevention and control as well as emergency response capabilities of warping dam projects in some areas are insufficient. This seriously affects the quality and function performance of warping dam projects.

4. Effective countermeasures for the construction of warping dam projects in the loess plateau area

4.1. Improve the planning system to realize the unity of "scientific layout" and "precise design"

Establishing a planning mechanism of "basin overall planning + regional adaptation" is the key to solving the planning and design problems of warping dam projects in the Loess Plateau area [11]. To this end, the overall plan for warping dam project construction should be formulated based on the conditions of the Yellow River tributaries. During this process, the construction scale, standards, and goals of warping dam projects in different river basins and regions should be clarified to implement the concept of "scientific layout". For example, in river basins with severe soil erosion such as the Wuding River, a "cascaded dam system" design should be adopted to increase the construction density of warping dam projects, thereby further highlighting their value in soil and water conservation. Secondly, systematic survey work should be carried out. For instance, a dedicated survey team can be organized to conduct detailed surveys and analyses of the hydrology, geomorphology, soil, climate, and other environmental conditions in the construction area. On this basis, warping dam projects that match and coordinate with the above factors should be built to ensure the scientificity and forward-looking nature of the project construction.

In addition, technologies such as BIM and artificial intelligence can be used to conduct model simulation and analysis for warping dam construction during this process, thereby further improving the adaptability and scientificity of the project construction [12]. Furthermore, the integration of warping dam projects with local industrial development should be considered. During the design process, full cooperation and planning with local agricultural, tourism, and other departments should be carried out to align the construction of warping dam projects with the advancement of the local rural revitalization strategy. For example, in areas with strong tourism development potential, facilities such as viewing platforms and running tracks can be planned and designed around warping dam projects to better meet the needs of local industrial development, maximize the radiating effect of warping dam projects, and achieve the goals of precise design and multi-party win-win.

4.2. Strengthen construction supervision to promote the coordination of "quality control" and "standard specification"

First, the access mechanism for construction units should be improved. For example, construction units must have relevant project experience or qualification to contract Grade III or above projects, and possess professional equipment and talents. This approach can effectively ensure the construction quality of warping dams. During the construction process, "third-party testing" can also be introduced to conduct full-process supervision of the construction process and ensure that the construction quality meets the standards. Secondly, the raw material quality inspection system should be improved. The application of raw materials in the construction of warping dams should be supervised throughout the process. Once quality problems are found, responsibility tracing should be carried out immediately.

On this basis, the scientificity and safety of raw material inventory should be ensured. For example, during the storage of cement, the warehouse should be treated to be rainproof and moisture-proof to ensure the quality of raw materials and their effective use in subsequent processes. Furthermore, the construction acceptance standards should be improved. Relevant departments can take the lead in accelerating the issuance of documents on the construction quality and acceptance standards for warping dams in the Loess Plateau, and clearly stipulate the quality indicators and technical requirements of the projects to ensure the construction quality of warping dam projects [13]. On this basis, attention should be paid to the dynamic update of standards. For example, relevant standards and specifications should be dynamically adjusted based on local climate change and technological development in the new era to comprehensively improve their timeliness and scientificity.

4.3. Optimize the management and protection mechanism to promote the combination of "responsibility implementation" and "fund guarantee"

First, it is necessary to clarify multiple management entities and further define the responsibilities of entities at all levels. For example, a diversified warping dam management and protection model can be established, with government departments as the leading force, village collectives as the main responsible parties, and professional institutions extensively participating. This model can give full play to the management and protection efficiency of multiple entities. On this basis, the specific responsibilities of each entity should be clarified. For instance, relevant government departments are responsible for regularly assigning professionals to conduct dam inspection work to prevent potential risks. Village collectives can set up their own dam protection teams to take charge of the daily maintenance and management of warping dams. Professional institutions such as water conservancy management departments can provide professional technical services for the repair and maintenance of warping dams. Second, it is essential to improve fund guarantees.

Relevant government departments should establish a stable fund investment mechanism based on the actual situation of warping dam construction in the Loess Plateau. At the same time, they should actively encourage social capital to participate in the construction, management, and protection of warping dams. Relevant enterprises or individuals should be allowed to develop characteristic tourism, agriculture, and other industries around warping dam construction. This can better expand fund sources and give play to the role of warping dam projects in promoting local agricultural economic development [14]. Furthermore, the supervisory role of the masses should be fully exerted to ensure that multiple entities fulfill their duties and minimize the safety risks of warping dams. During this process, it is necessary to strengthen publicity and education for the masses. Village radio broadcasts, self-media communication, and other methods can be used to popularize knowledge about the construction, management, and protection of warping dams among local people. This will enhance their awareness of management, protection, and supervision, and create a good atmosphere where "everyone participates in management and protection, and everyone supervises management and protection".

4.4. Improve monitoring and early warning to realize joint efforts of "real-time monitoring" and "risk prevention and control"

To address problems in monitoring and early warning, the construction of warping dam projects in the Loess Plateau should continuously improve the monitoring and early warning mechanism. First, it is necessary to optimize the layout design of monitoring points to ensure full coverage. On this basis, digital technologies should be actively introduced to improve the timeliness and flexibility of monitoring and early warning. At the same time, modern digital platforms should be used to realize real-time sharing of warping dam monitoring and early warning information. This can avoid the problem of information silos that existed in previous manual monitoring and early warning [15]. Second, it is important to improve monitoring indicators and focus on comprehensive project benefit evaluation. For example, comprehensive monitoring and analysis should be conducted on local soil and water conservation, agricultural economic development, and other aspects. This will form a comprehensive monitoring report and lay an information foundation for the optimization and improvement of warping dam project construction.

Furthermore, it is necessary to optimize and upgrade the early warning system and early warning plans. For instance, a digital automatic early warning system can be introduced to monitor the operation status of warping dam projects in real time. An intelligent analysis system can be adopted to conduct intelligent analysis of monitoring data, detect potential risks in a timely manner, and then carry out effective handling and response.

In addition, it is also necessary to design and improve emergency plans, formulate early warning mechanisms for various emergencies and risks, clarify relevant handling procedures and main responsibilities, and regularly organize multiple entities to carry out emergency drills. This can comprehensively improve the coordination effect of various entities in risk prevention and control and effectively reduce the incidence of risk problems.

5. Conclusion

In general, there are certain practical problems in the construction of warping dam projects in the Loess Plateau area in the new era. In this regard, while scientifically analyzing these problems, we should constantly use new methods and countermeasures to improve the scientificity and effectiveness of warping dam project construction. This will enable warping dam projects to better play their roles and values, and lay a solid foundation for the realization of harmonious coexistence between humans and nature in the Loess Plateau area.

Disclosure statement

The author declares no conflict of interest.

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Stability Analysis and Safety Evaluation of Surrounding Rock in Shallow-buried Concealed Tunnel Construction

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Abstract: In the construction of shallow-buried concealed tunnels, the control of surrounding rock stability is a core challenge, which is crucial to construction safety and structural performance. A two-dimensional model was established using Midas GTS NX, combined with bench cut method excavation simulation. The laws of vault and surface settlement were quantitatively analyzed through displacement nephograms, and the spatiotemporal characteristics of surrounding rock displacement were revealed. The results show that under the established excavation and support measures, the displacement and settlement meet the specification requirements. Meanwhile, the Analytic Hierarchy Process (AHP) was introduced to determine weights and analyze the coupling correlation of factors through judgment matrices, clarifying the influence degrees of surrounding rock grade, support strength, and other factors to achieve multi-dimensional evaluation. Furthermore, the Fuzzy Comprehensive Evaluation method was integrated to quantify the mapping relationship between surrounding rock stability and safety, and the safety grade was obtained. Finally, measures such as strengthening support, optimizing excavation parameters, refined exploration, and improving management were proposed to enhance surrounding rock stability and reduce construction risks.

Keywords: Shallow-buried concealed excavation; Surrounding rock stability; Bench cut method; FAHP

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1. Introduction

In the construction of shallow-buried concealed tunnels, controlling surrounding rock stability is a core challenge that is critical to construction safety and structural performance. The shallow burial depth renders the surrounding rock mechanically vulnerable, and excavation is prone to inducing vault settlement and surface deformation. If surface settlement exceeds the allowable limit during construction, it will not only affect the flatness of hub functional areas or the construction accuracy of ongoing facilities but may also lead to construction suspension for remediation, resulting in project delays and substantial economic losses.

In the field of surface settlement prediction for shallow-buried tunnels, Peck proposed a classic empirical formula for estimating the volume of settlement trough based on the concept of ground loss using a large amount of measured data, which has become a commonly used method for surface settlement prediction in engineering [1].

O'Reilly supplemented through research on the settlement characteristics of clay and sand that the width coefficient of the settlement trough increases with the tunnel burial depth. In studies on special scenarios and model optimization, Saeid R proposed a Shallow Tunnel Classification System (STCS) based on the maximum settlement value, evaluating tunnel stability by integrating parameters such as burial depth and diameter [2,3]. She Fangtao et al. modified the traditional curve function for loess strata, improving the accuracy of longitudinal settlement description [4].

Xudong Wang et al. established a two-dimensional settlement propagation model based on the random medium theory, incorporating the randomness and inhomogeneity of soil layers to enhance prediction accuracy [5]. Dechun Lu et al. constructed a unified displacement function for circular tunnel sections, clarifying the law that vault settlement is greater than bottom rebound [6].

In terms of surrounding rock stability analysis, Cao Shiwei established a relational model including flatness ratio and bias pressure angle, revealing the correlation between tunnel failure modes and surrounding rock pressure [7]. Xie Jiajie proposed a surrounding rock stress calculation formula covering multiple factors such as ground load and support structure [8]. Regarding the application of numerical simulation technology, Guan Hongbing, Zhu Yongxiang et al. used FLAC 3D to simulate double-line shield tunnels, obtaining the laws of surface settlement curves [9]. Wang Jinhua conducted stochastic finite element analysis by combining ABAQUS and Matlab, verifying the consistency of settlement curve calculations [10].

Zhu Bin explored the disturbance characteristics of soil caused by overlapping tunnel construction using Midas software [11]. In field monitoring research, Yang Haiqin et al. confirmed the consistent downward trend of surface and vault settlement through comparison [12]. Cheng Zhengmin et al. obtained the excavation displacement laws of large-section variable-cross-section tunnels using the CRD method [13]. Miao Xueyun et al. acquired data on surface settlement, surrounding rock moisture content, and steel arch stress through testing components for tunnels in the loess tableland area [14].

Current research mostly focuses on ordinary shallow-buried tunnels, lacking special analysis for hub core area scenarios. Key construction issues such as the adaptive selection of excavation methods, the matching accuracy between numerical simulation parameters and hub strata, and the quantitative evaluation of "surrounding rock deformation, construction safety" still need in-depth exploration, which is difficult to fully meet the requirements of safe and efficient tunnel construction.

2. Project overview and construction simulation

2.1. Project overview

The research object is a shallow-buried concealed tunnel constructed by the bench cut method, with two main tunnels (left and right). Each tunnel has a net width of 18.5 m and a clear height of 5 m, with uniform structural dimensions to meet the engineering design load and traffic requirements. Before excavation, the outer contour of the tunnel and the middle internal bracing were poured in the soil using C40 concrete.

After pouring, taking the boundary between the silty clay layer and the coarse gravel layer as the dividing line, the upper and lower bench cut method was adopted for excavation, following the sequence: left half of the upper bench, left half of the lower bench, right half of the upper bench, and right half of the lower bench.

The exposed strata from top to bottom are Quaternary surface layer (fill soil, miscellaneous fill), alluvial-proluvial layer, eluvial-slope wash layer, and Carboniferous Shidengzi Formation bedrock, with significant differences in engineering mechanical properties among each layer.

2.2. Construction simulation

For the shallow-buried concealed section of the North Airport Tunnel, this study used GTS NX to establish a 2D model to simulate bench cut excavation.

Based on Saint-Venant's principle and the 18.5 m net width of the tunnel, the model was set to 100 m in length and 33.8 m in width. Since the distance from the tunnel top to the ground surface is only 6.25 m, the silty clay within 50 m on both sides of the central axis was reinforced by grouting with C20 concrete [15].

The Mohr-Coulomb model was applied to the soil layers, with parameters shown in the **Table 1** and **Figure 1** below.

Table 1. Mechanical parameters of each rock-soil layer and material

Rock-soil layer or material	Elastic modulus (kPa)	Poisson's ratio μ	Unit weight (kN/m³)	Cohesion C (MPa)	Internal friction angle φ (°)
Silty clay	50	0.3	15	22	11
Coarse gravel sand	100	0.3	16.5	5	20
Strongly weathered argillaceous siltstone	200	0.34	22	10	25
C20 grouted soil layer	500	0.2	22	10	23
C40	30	0.2	26	—	—

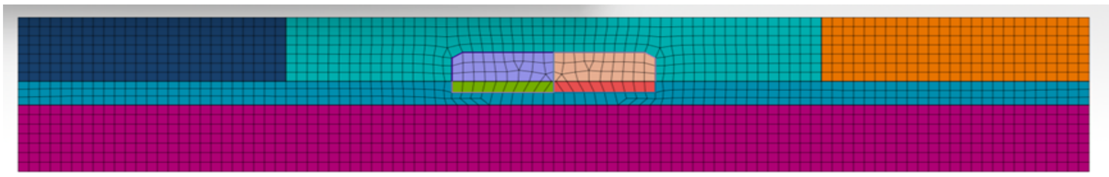

Figure 1. Tunnel construction model.

2.3. Analysis of simulation results

(1) Excavation of the left upper bench

It showed the characteristics of "upper settlement and lower heave". The maximum settlement above was 17.70 mm, the heave below was 7.53 mm, and the surface settlement was 12.6 mm. The settlement increased with the burial depth up to the tunnel top; only the left soil showed slight displacement.

(2) Excavation of the left lower bench

The deformation mode remained unchanged, but the displacement decreased. The maximum upper settlement was 16.38 mm, the lower heave was 5.76 mm, and the surface settlement was 11.3 mm.

(3) Excavation of the right upper bench

The "upper settlement and lower heave" pattern persisted. The upper settlement on the left was 14.59 mm and on the right was 13.6 mm; the lower heave on the right was 7.70 mm. The surface settlements on the left and right were 9.5 mm and 10.1 mm, respectively. The settlement increased with the burial depth up to the tunnel top, with only slight displacement on the right.

(4) Excavation of the right lower bench

The displacement further decreased. The top settlements on the left and right were 13.96 mm and 12.2 mm; the lower heaves were 5.2 mm and 4.9 mm; the displacements on both sides were 3.34 mm and 3.35 mm (basically symmetrical).

In summary, the entire excavation process was dominated by "upper settlement and lower heave", with displacement decreasing as excavation progressed. Surface settlement was significantly affected by shallow burial, while disturbances on both sides were small, verifying that the “support-first, excavation-later” approach is effective in controlling deformation.

3. Risk evaluation of surrounding rock stability in shallow-buried concealed tunnels based on FAHP

3.1. Determination of evaluation index weights

Following the core principle of the Analytic Hierarchy Process (AHP) – “focusing on dominant factors and ignoring secondary ones” – key control factors were extracted from numerous factors affecting tunnel excavation. Finally, a risk evaluation system for shallow-buried concealed tunnel construction was established, including 5 secondary indicators and 17 tertiary indicators.

Combined with actual conditions, comparisons were made between each index in the criterion layer and each factor within the criterion layer to obtain the judgment matrices of evaluation indicators for the criterion layer and the scheme layer. Weight vectors were calculated based on the judgment matrices at all levels, and consistency tests were conducted on the judgment matrices.

Judgment Matrix of Criterion Layer Evaluation Indicators

$$A_0 = \begin{pmatrix} 1 & 1/5 & 1/3 & 1/2 & 1/4 \\ 5 & 1 & 3 & 5 & 2 \\ 3 & 1/3 & 1 & 2 & 1/2 \\ 2 & 1/5 & 1/2 & 1 & 1/3 \\ 4 & 1/2 & 2 & 3 & 1 \end{pmatrix}$$

The maximum eigenvalue and the corresponding eigenvector that can be obtained through calculation

$$\lambda_{0\max} = 5.0682$$

$$a_0 = (0.1138, 0.8012, 0.2925, 0.1706, 0.4800)$$

The weight vector is obtained after normalization

$$\omega_0 = (0.0613, 0.4312, 0.1574, 0.0918, 0.2583)^T$$

$CI = 0.0170$, $RI = 1.12$, and $CR = 0.0152$ are calculated, so A meets the requirements, and this result can be used as the final decision weight.

Similarly, the consistency of the judgment matrices for the evaluation indicators in the scheme layer all meet the requirements. Based on the calculated weights of each factor, the excavation section size has the greatest impact, followed by vault settlement, while precipitation has the smallest impact, with the influence degrees of other factors falling in between.

3.2. Fuzzy-based construction safety risk analysis of shallow-buried concealed tunnels

To comprehensively evaluate the construction and excavation risks of shallow-buried concealed tunnels, this study refines several scheme layer indicators from multiple criterion layers (such as hydrogeological conditions and tunnel design conditions). It classifies the risk occurrence levels (e.g., “very likely”, “likely”) under each indicator and establishes the judgment matrix for the scheme layer.

The fuzzy synthesis operation for hydrogeological conditions is calculated as follows.

$$A_1 = \begin{pmatrix} 0 & 0.1 & 0.7 & 0.2 & 0 \\ 0 & 0.4 & 0.5 & 0.1 & 0 \\ 0 & 0.3 & 0.5 & 0.2 & 0 \\ 0 & 0.2 & 0.6 & 0.2 & 0 \end{pmatrix}$$

$$\omega_1 = (0.0721, 0.4761, 0.2471, 0.2047)$$

$$S_1 = \omega_1 \times A_1 = [0, 0.3127, 0.5349, 0.1524, 0]$$

Similarly, the fuzzy comprehensive evaluation for other criterion layers can be obtained. Then, a multi-level fuzzy comprehensive evaluation is conducted on them.

$$A = \begin{pmatrix} 0 & 0.3127 & 0.5349 & 0.1524 & 0 \\ 0 & 0.3763 & 0.5000 & 0.1172 & 0.0065 \\ 0 & 0.3526 & 0.4352 & 0.2000 & 0.0122 \\ 0 & 0.0742 & 0.6000 & 0.2000 & 0.1258 \\ 0 & 0.3649 & 0.5351 & 0.1000 & 0 \end{pmatrix}$$

$$\omega_0 = (0.0613, 0.4312, 0.1574, 0.0918, 0.2583)^T$$

$$S = \omega_0 \times A = [0, 0.3380, 0.5102, 0.1355, 0.0163]$$

The comprehensive evaluation result of the excavation risk of the shallow-buried concealed tunnel is obtained. This design adopts the principle of maximum membership degree, with the risk level value being 0.5102, corresponding to the risk evaluation result of "accidental".

4. Conclusion

To address the issue of risk management and control in the excavation of shallow-buried concealed tunnels, this study first identified key risk factors and constructed an evaluation system through literature research combined with engineering practice. Then, it established a risk evaluation system based on the Analytic Hierarchy Process (AHP), coupled with the fuzzy comprehensive evaluation method to quantify the risk level, and formed a control scheme.

The core results are as follows.

(1) Midas GTS NX simulation shows that after the excavation of this large-section tunnel, the top settlement and bottom heave are significant, and both decrease with the progress of excavation

(2) An evaluation index system including 5 criterion layers and 17 scheme layer factors was constructed. Weight calculation indicates that 5 factors such as excavation section size and vault settlement are core risk factors; after dividing the risk levels through fuzzy comprehensive evaluation, protective measures were proposed in combination with risk characteristics, providing support for construction safety.

Disclosure statement

The author declares no conflict of interest.

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Multi-Source Heterogeneous Data Fusion Analysis Platform for Thermal Power Plants

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Abstract: With the acceleration of intelligent transformation of energy system, the monitoring of equipment operation status and optimization of production process in thermal power plants face the challenge of multi-source heterogeneous data integration. In view of the heterogeneous characteristics of physical sensor data, including temperature, vibration and pressure that generated by boilers, steam turbines and other key equipment and real-time working condition data of SCADA system, this paper proposes a multi-source heterogeneous data fusion and analysis platform for thermal power plants based on edge computing and deep learning. By constructing a multi-level fusion architecture, the platform adopts dynamic weight allocation strategy and 5D digital twin model to realize the collaborative analysis of physical sensor data, simulation calculation results and expert knowledge. The data fusion module combines Kalman filter, wavelet transform and Bayesian estimation method to solve the problem of data time series alignment and dimension difference. Simulation results show that the data fusion accuracy can be improved to more than 98%, and the calculation delay can be controlled within 500 ms. The data analysis module integrates Dymola simulation model and AERMOD pollutant diffusion model, supports the cascade analysis of boiler combustion efficiency prediction and flue gas emission monitoring, system response time is less than 2 seconds, and data consistency verification accuracy reaches 99.5%.

Keyword: Thermal power plant; Multi-source heterogeneous data; Data fusion analysis platform; Edge computing

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1. Introduction

With the transformation of energy system to intelligent and efficient, thermal power plant, as the core infrastructure to ensure energy security, its equipment operation status monitoring and production process optimization has become the focus of the industry. In complex thermal cycle systems, the operation parameters, environmental data and operation and maintenance records of key equipment such as boiler, steam turbine and generator are heterogeneous from multiple sources. Traditional single-dimensional data analysis methods cannot meet the requirements of equipment life cycle management. By integrating data from physical sensors (temperature, vibration, pressure) with real-time operational data from SCADA systems, multi-source heterogeneous data fusion technology overcomes the limitations of single-source information, providing comprehensive decision support for equipment fault prediction and energy efficiency optimization [1]. For example, the fusion of infrared thermal imaging and 3d spatial data has been proven to have significant advantages in defect location and maintenance efficiency improvement in the monitoring of solar power plant equipment, and this cross-modal data integration strategy can also be applied to the state assessment of core equipment in thermal power plants.

2. Design of multi-source heterogeneous data fusion analysis platform for thermal power plants

2.1. Design of data fusion module

As the core component of the thermal power plant multi-source heterogeneous data fusion and analysis platform, the data fusion module should be designed to take into account the diversity of data collection, real-time processing and accuracy of analysis. This module establishes a multi-layered integrated architecture to enable deep interaction between physical and information spaces, ensuring effective integration of heterogeneous data from sensor networks, historical databases, and external systems. In the design process, based on the theoretical framework of data fusion, multi-dimensional data calibration and dynamic weight allocation strategy are adopted to solve the differences of different data sources in time series, format and dimension. In order to improve the data quality, the module introduces the abnormal detection algorithm based on physical constraints, and establishes the multi-parameter correlation model based on the operation mechanism of thermal power units, which can effectively eliminate the noise data and correct the measurement deviation.

In terms of implementation, the module first accesses various data sources through standardized interface protocols, including real-time sensor signals such as temperature, pressure and flow, as well as structured data from SCADA systems. To address the spatiotemporal alignment requirements of heterogeneous data, we employ time series interpolation and spatial coordinate mapping techniques to unify multi-source data under a unified spatiotemporal reference framework [2,3]. Subsequently, a 5D model based on digital twin technology establishes a mapping relationship between physical and virtual spaces. The physical model describes the unit’s operational status, while the virtual model is updated in real-time through data fusion results, enabling bidirectional information flow interaction. This model integrates physical sensor data, simulation calculation results, and expert knowledge, forming a collaborative analysis foundation for multi-source information.

2.2. Data analysis and visualization module design

As the core function unit of the multi-source heterogeneous data fusion and analysis platform for thermal power plants, the data analysis and visualization module is mainly responsible for data processing, intelligent analysis and multi-dimensional visualization. The module is built on a B/S architecture, and the hierarchical design realizes the integration of the whole process of data collection, storage, calculation and display. The technical implementation fully integrates dynamic modeling, real-time communication and interactive visualization. At the data processing level, the module design includes data preprocessing, feature extraction and standardized transformation, which can effectively deal with the format difference and noise interference of multi-source heterogeneous data in the production process of thermal power plant. The system facilitates data exchange with underlying systems like DCS and SCADA through Web service interfaces, using XML for standardized data formats. By leveraging Ajax technology, it enhances real-time responsiveness on the client side, ensuring stable and timely data collection and transmission.

The data analysis module adopts a hybrid modeling strategy, which includes traditional methods such as statistical analysis and association mining, and integrates machine learning algorithms for complex pattern recognition. For example, to meet the dynamic monitoring requirements of key parameters such as boiler combustion efficiency and steam turbine vibration characteristics, the system introduced a simulation model developed on the Dymola platform.

Through comparison and verification with measured data, the system achieved high-precision prediction of equipment operating status. For multi-source data fusion analysis, the system adopts a cascaded modular architecture. Each data processing unit performs specific functions independently: the flue gas emission monitoring module integrates the AERMOD model for pollutant diffusion simulation, while the thermal system module achieves coordinated analysis of energy and material flows through a cascaded topology [4]. This modular design not only improves the scalability of the system, but also supports flexible configuration of the analysis process according to actual needs. For example, in the scenario of joint optimization scheduling, the system can call the wind power probability prediction model and thermal power load allocation algorithm to generate multi-objective optimization scheduling scheme.

3. Data collection and processing

3.1. Data collection methods

The data collection system design of the multi-source heterogeneous data fusion analysis platform for thermal power plants follows the principles of full life cycle coverage, multi-dimensional fusion and high real-time, and builds a distributed data acquisition architecture. The data sources of the platform include various heterogeneous data sources such as unit operation parameters, environmental monitoring data, equipment status information, production management records, and external meteorological energy data. The system implements a hierarchical data collection strategy tailored to different data sources. For time-series data requiring real-time processing, it establishes bidirectional communication interfaces with power plant DCS and SCADA systems via OPC UA protocol, enabling millisecond-level acquisition of critical parameters such as temperature, pressure, and flow rate from core equipment including boilers, steam turbines, and generators; For unstructured manual inspection records and equipment maintenance logs, structured processing is performed through customized data entry interfaces, utilizing natural language processing technology to extract key information fields. For third-party data sources such as environmental monitoring systems, standardized API interfaces and HTTPS encrypted transmission protocols are employed to ensure data integrity and security during collection.

In the data acquisition process, the system sets up a three-level quality assurance mechanism. First, the redundant sensors and intelligent gateway at the hardware layer realize the preliminary verification of the data source, and the adaptive filtering algorithm is used to eliminate the high-frequency noise interference. Secondly, the QoS Level 2 service quality is implemented at the transport layer using the MQTT protocol, ensuring transmission reliability through heartbeat packet detection and data packet retransmission mechanisms. Finally, a data preprocessing module is deployed on the edge computing node to perform timestamp synchronization, dimensionality unification, and format standardization on the collected raw data. For historical data requiring protocol conversion, the system employs ETL tools to transform industrial protocols such as Modbus, Profibus into standard JSON format, while establishing a data dictionary to map physical quantities to business semantics [5].

3.2. Data preprocessing and cleaning

In the process of data standardization and normalization, appropriate transformation strategies should be selected according to the distribution characteristics of different data types. For continuous variables, Z-score normalization is employed to eliminate dimensional differences, with the formula: where μ and σ represent the sample mean and standard deviation, respectively. Discrete variables are converted into numerical features through one-hot encoding. For text-based device status description data, a structured conversion process based on natural language processing is established to extract key semantic features through regular expressions and map them to a predefined classification coding system. In terms of data quality assessment, a multi-dimensional quality index system is constructed, including key indicators such as data integrity (missing rate < 0.5%), consistency (cross-system data deviation < 3%), timeliness (delay time < 10 seconds), etc., and the credibility of data is quantified by the quality scoring model [6]. To address format heterogeneity, ETL (Extract-Transform-Load) tools are employed to standardize data formats, including XML, CSV, and database tables. A metadata catalog is established to document source information such as data origin, collection time, and sensor model.

4. Experiment and analysis

4.1. Experimental methods and steps

This study takes the typical operation scenario of thermal power plant as the background, and adopts the multi-source heterogeneous data fusion analysis platform to carry out collaborative analysis of boiler combustion system, steam turbine power generation system and environmental monitoring system. The experiment design follows the whole process framework of “data collection, preprocessing, fusion modeling, verification and evaluation”, and focuses on verifying the technical effectiveness of the platform in data space-time alignment, feature extraction and dynamic modeling.

The experimental data collection employed a hierarchical heterogeneous strategy. First, the SCADA system captured 32 types of time-series data (including boiler main steam temperature and pressure) with 1-second sampling intervals. Simultaneously, process parameters such as coal feed rate and air volume from the DCS system were sampled at 5-second intervals, while NOx emission concentration data from environmental monitoring stations were recorded every 10 minutes [7]. To ensure data integrity, a spatiotemporal reference coordinate system with multi-source data was established. All sensor devices were synchronized using GPS clocks, and data with different sampling frequencies were time-aligned through cubic spline interpolation. For unstructured data such as boiler endoscope video streams, the YOLOv5 model is employed to perform semantic segmentation of critical equipment components and extract flame morphology parameters.

4.2. Experimental results and analysis

In this experiment, a prototype system of multi-source heterogeneous data fusion analysis platform was constructed and tested in the actual operation environment of a 300MW thermal power unit, focusing on the performance of the platform in data integration efficiency, model prediction accuracy and system response performance. The experimental data included real-time sensor data from equipment such as boilers, steam turbines, and auxiliary systems, as well as historical operation records from SCADA systems, DCS control commands, and external meteorological data, with a total of about 2.5 million valid data samples collected. The cross-validation method is used to verify the performance of the fusion algorithm and compare the difference with the traditional single source data analysis method.

At the data fusion level, the platform employs ETL processes to convert data from multiple formats (including Modbus, OPC UA, and CSV) into standardized time-series sequences. The data cleansing module successfully identified and corrected 12.7% of outliers and missing data. In the feature engineering process, the sliding window method was used to extract time series features, and the fusion feature vector containing 42 dimensions was constructed by combining the statistics and frequency domain analysis. Experimental results show that after multi-source data fusion, the RMSE value of the boiler thermal efficiency prediction model decreased from 1.8% to 1.1% compared with single-source data, and the AUC value of steam turbine vibration prediction increased to 0.89, which is significantly better than the reference value of 0.76 of single sensor data [8].

5. Conclusion

In view of the urgent need for multi-source heterogeneous data fusion and analysis in thermal power plants, this study constructs an intelligent analysis platform based on edge computing and deep learning, whose core achievements are reflected in three aspects: technological system innovation, data processing capability improvement and engineering application value. By integrating data from SCADA systems, DCS control units, environmental monitoring devices, and IoT sensors, the platform has established a cross-level data fusion architecture for thermal cycles, combustion optimization, and equipment condition monitoring. This effectively resolves issues such as data silos, heterogeneous protocols, and insufficient real-time performance in traditional systems. At the data acquisition layer, a dynamic adaptation interface supporting OPC UA, Modbus TCP, MQTT and other protocols was developed to achieve millisecond-level collection and standardized conversion of key parameters of thermal power units (such as main steam temperature, boiler efficiency, pollutant emission concentration), with data integrity reaching more than 99.2%.

Disclosure statement

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Research on the Application of Digital Twin Technology in the Full Lifecycle Operation and Maintenance Management of Urban Road Infrastructure

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Abstract: With the continuous development of digital technology, urban management and urban construction have undergone tremendous changes, exerting a profound impact on people's lives. As a vital component of cities, urban road infrastructure is closely related to the daily lives of citizens. The application of digital twin technology can provide more support for the full lifecycle operation and maintenance management of urban road infrastructure, effectively improving the quality and efficiency of operation and maintenance management, ensuring the effectiveness of urban road infrastructure, and building a higher-quality urban life. Based on urban road infrastructure, this paper analyzes the application value of digital twin technology, proposes strategies for full lifecycle operation and maintenance management, and offers more references for urban construction.

Keywords: Digital twin technology; Urban roads; Infrastructure; Full lifecycle; Operation and maintenance management

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1. Introduction

The full lifecycle operation and maintenance management of urban road infrastructure is a comprehensive and complex management task that involves various stages, including planning, design, construction, operation, and maintenance of the infrastructure. With the accelerating process of urbanization, the demand for urban road infrastructure is also growing, highlighting the importance of its full lifecycle operation and maintenance management. Through the application of digital twin technology, real-time monitoring of the status and performance of urban road infrastructure can be achieved, enabling timely identification of issues and the implementation of targeted solutions. This promotes the construction of smart cities and provides citizens with more comfortable urban services.

1.1. Overview of digital twin technology

Digital twin technology is a product of the continuous development of digital technology. It creates corresponding virtual replicas for physical entities and uses them as platforms to effectively monitor the actual behavior and performance of these entities, thereby enabling analysis and evaluation. The concept of digital twins was first proposed by Michael Grieves in 2002 within the context of Product Lifecycle Management (PLM), and has since gradually been promoted and applied in fields such as aerospace and manufacturing [1,2]. Today, with the continuous development of artificial intelligence technology, the gradual popularization of Internet of Things technology, and the increasing maturity of big data technology, the application scope of digital twin technology has become increasingly widespread. It has become an indispensable tool for urban infrastructure management, providing more assistance to urban construction [3].

2. Application significance of digital twin technology

2.1. Improving the quality and efficiency of operation and maintenance management

Digital twin technology can provide managers with a 1:1 accurate model of urban road infrastructure, helping them more efficiently conduct performance tests on the infrastructure, design targeted operation and maintenance plans, reduce unscientific maintenance measures, ensure the efficient and high-quality operation of various infrastructure, and promote continuous improvement in the quality and efficiency of operation and maintenance management.

2.2. Ensuring the safety and reliability of operation and maintenance management

Digital twin technology can establish a real-time, dynamic monitoring system for urban road infrastructure. Through sensor networks deployed in structures such as roads, bridges, and tunnels, the system can continuously collect operational data such as deformation, stress, displacement, temperature, and humidity, and then conduct intelligent analysis and risk assessment of the operational status of the facilities. When abnormal fluctuations in monitoring data occur, the system can immediately generate warning signals, prompting managers to take targeted actions, thereby effectively reducing the probability of safety accidents.

Meanwhile, through the joint analysis of historical operational data and simulation models, the digital twin platform can identify high-risk areas and vulnerable components within the facilities, assisting management departments in formulating scientific inspection and maintenance plans. This data-driven dynamic monitoring mechanism not only enhances the real-time nature and accuracy of operations and maintenance but also provides reliable assurance for the long-term stable operation of urban infrastructure.

2.3. Achieving optimal allocation of operations and maintenance management resources

Digital twin technology can integrate with the actual conditions of urban road infrastructure operations and maintenance management to achieve optimal resource allocation, ensuring the quality of operations and maintenance management. This allows infrastructure to operate in its best possible state, providing greater assistance to urban residents in their travels. The system can scientifically allocate maintenance personnel, equipment, and financial investments based on the importance of facilities, operational loads, and risk levels, avoiding resource wastage and redundant operations. Additionally, the digital twin platform supports a quantitative evaluation mechanism based on ROI (Return on Investment), helping managers assess the input-output ratio of various operations and maintenance plans from an economic perspective and providing quantitative evidence for decision-making in urban infrastructure management. This data-driven refined management model not only improves the efficiency of operations and maintenance resource utilization but also promotes the sustainable development of the urban infrastructure operations and maintenance system [4].

3. Application of digital twin technology

3.1. Application in urban road infrastructure construction

3.1.1. Design phase

During the design phase of urban road infrastructure construction, digital twin technology can assist designers in optimizing design plans more conveniently [5]. Designers can use digital twin technology to create models of urban road infrastructure based on design requirements, analyzing potential climate conditions, usage requirements, and maintenance needs that the infrastructure may face in different virtual environments. By comparing the advantages and disadvantages of different design plans, designers can promptly identify issues and deficiencies in the design plans and take targeted measures for optimization. Through this virtual experimentation approach, design flaws can be identified in advance, construction rework can be minimized, construction costs can be reduced, and project timelines can be shortened [6].

Digital twin technology can also facilitate multidisciplinary collaboration in the design process of urban road infrastructure, enabling designers to complete scheme designs more efficiently. Urban road infrastructure is a comprehensive project that requires the joint participation of professionals from various fields, such as structural engineering and civil engineering. On the digital twin platform, engineers from different disciplines can enter the same virtual environment, enabling real-time information sharing and jointly driving continuous design optimization. This approach helps overcome information silos in traditional design models, further enhancing the feasibility of design schemes and promoting the continuous improvement of urban road infrastructure [7].

The design drawings completed through digital twin technology can also provide more comprehensive technical support for subsequent construction and operation and maintenance. During the design phase, designers need to consider the requirements for the operation and maintenance of urban road infrastructure throughout its entire lifecycle and incorporate potential maintenance issues into the design model. This approach allows for corresponding optimizations during the construction phase and facilitates the design of emergency response plans within the system, enabling timely access in case of unexpected issues and effectively mitigating severe consequences [8].

Additionally, operation and maintenance personnel can accurately understand the structure and function of various infrastructure components based on the system models uploaded by designers on the platform, thereby improving the quality and efficiency of infrastructure operations and ensuring that the overall performance of the infrastructure better meets the needs of different groups.

3.1.2. Construction phase

Digital twin technology enables real-time monitoring of the construction process of urban road infrastructure and simulates subsequent construction procedures through virtual simulation. This not only provides more precise guidance for construction but also significantly enhances construction efficiency and quality [9]. Construction personnel can also leverage digital twin technology platforms to simulate and analyze potential construction issues that may arise in the future, effectively predicting risks inherent in the construction process. This enables the formulation of more targeted strategies, ensuring the quality of urban road infrastructure construction and laying a solid foundation for subsequent operation and maintenance efforts.

Digital twin technology also facilitates the real-time collection of various types of data during the construction process and enables rapid sharing within the platform. Numerous sensors are often installed at construction sites, transmitting real-time construction data to the digital twin platform. Models are then constructed based on construction drawings and specific progress, allowing managers to visually observe the construction status of road infrastructure and evaluate construction effectiveness. This facilitates timely adjustments to construction plans in line with project deadlines and usage requirements [10].

Digital twin technology also provides construction personnel with a more convenient environment and conditions for equipment learning. On the platform, construction personnel can use virtual models to practice operating specific equipment, enabling them to better familiarize themselves with operational processes and related techniques while also mastering necessary emergency response measures. As a result, construction personnel can approach actual construction with confidence and promptly address unexpected situations, preventing any adverse impact on infrastructure projects [11].

Additionally, based on the construction needs of different infrastructure projects, digital twin technology can monitor the usage of various resources in real time, providing more comprehensive resource allocation plans in line with construction progress to ensure the efficient utilization of engineering resources. This not only significantly enhances construction quality and efficiency but also facilitates the operation and maintenance management of urban road infrastructure, effectively reducing cost consumption during the operation and maintenance process.

3.1.3. Operation and maintenance phase

Upon completion of construction, digital twin technology can conduct real-time analysis of the operational status of infrastructure, effectively monitoring the performance of various facilities and equipment. This can not only help operation and maintenance personnel more accurately grasp the basic structure and main functions of infrastructure, but also enable them to understand the service effectiveness of the infrastructure, so as to adopt more targeted strategies to design maintenance plans and effectively establish a virtuous cycle of operation and maintenance. Under this real-time monitoring mode, operation and maintenance personnel can not only detect abnormal phenomena in facilities and equipment, but also observe the status of these new facilities and equipment in the surrounding environment, so as to assess whether further environmental modifications and optimizations are required, thereby effectively reducing safety risks arising during the operation of infrastructure [12].

Digital twin technology can also predict the lifecycle of infrastructure. By combining relevant historical usage data and equipment performance reports, it can predict potential future failures through computational models and design more targeted maintenance plans, thereby supporting the extension of the service life of infrastructure.

3.2. Application in the maintenance and repair of urban road infrastructure

Maintenance and repair work is a crucial aspect of the entire lifecycle operation and maintenance of urban road infrastructure, largely determining its service effectiveness and lifespan. Therefore, through the application of digital twin technology, infrastructure can be maintained in a relatively good operational state, laying the foundation for improving urban service quality [13].

3.2.1. Preventive maintenance

Preventive maintenance is a key focus in infrastructure operation and management, requiring managers to regularly inspect the basic status of infrastructure during daily operations and take corresponding maintenance measures to ensure that equipment performance remains stable and good. The application of digital twin technology can further enhance the quality and efficiency of preventive maintenance. Building digital twin models on the platform enables effective monitoring of operational parameters for various infrastructure facilities, such as temperature, humidity, vibration, and so on. When abnormal values are detected, the system automatically sends alerts to management personnel and indicates the locations where the abnormal values have occurred, helping managers quickly locate and inspect them so that effective remedial measures can be taken.

Digital twin technology also enables managers to conduct in-depth analysis of historical data to explore the historical operational status of urban road infrastructure. For example, by combining historical maintenance records, managers can understand the main fault issues of the infrastructure and evaluate its overall operational performance through historical operational data. This approach allows for more precise identification of potential risks in the infrastructure and summarizes early characteristics of various faults, thereby facilitating more effective implementation of preventive maintenance and avoiding severe consequences caused by sudden failures [14].

Additionally, digital twin technology facilitates remote diagnosis and maintenance. Maintenance personnel can directly observe the actual state of the infrastructure through virtual models and perform remote operations via technical platforms. By leveraging the self-diagnostic capabilities provided by digital twin technology, they can more quickly locate faulty components in the infrastructure and complete repairs through remote guidance or operations, accelerating the restoration of infrastructure operations. This maintenance model not only reduces the time required for fault diagnosis but also lowers labor costs, enabling 24/7 uninterrupted monitoring of infrastructure. It ensures the normal operation of infrastructure and enhances urban service levels.

3.2.2. Emergency response

Emergency response is also a crucial aspect of the full lifecycle operation and maintenance of infrastructure, with digital twin technology further enhancing its efficiency. Digital twin models can directly provide managers with real-time parameters and status of infrastructure operations in the event of an emergency, helping them quickly grasp changes in the surrounding environment of the infrastructure, the functional status of its internal structure, and its operational conditions, among others. This enables managers to make rapid emergency decisions and formulate more efficient rescue and recovery plans.

Digital twin technology can also provide emergency response teams with different simulation scenarios to help them evaluate potential infrastructure failures and their consequences under various scenarios. This allows for the quickest possible response to rescue and fault handling in real-life scenarios that may arise in the future [15]. This not only significantly improves the reaction speed of emergency response teams but also ensures the accuracy of their emergency handling, effectively reducing losses and social impacts caused by emergencies. Additionally, digital twin technology can provide dynamically adjustable handling plans for emergency response teams based on the specific implementation of emergency responses, ensuring optimal allocation of resources and helping teams restore normal operation of various infrastructures more quickly.

Digital twin technology can not only provide emergency response teams with real-time captured on-site videos but also offer various precise data references through on-site sensors. It can also generate historical operation reports of infrastructure to help teams analyze the causes of infrastructure failures from different perspectives, more accurately determine maintenance considerations and potential risks, and provide scientific guidance for emergency actions. Furthermore, digital twin technology can provide remote command functions for emergency response services, allowing emergency personnel to further enhance the quality and efficiency of fault handling through remote guidance, providing more assistance in restoring road infrastructure to normal operation.

3.2.3. Performance optimization

Performance optimization is also an important aspect of the lifecycle management and operation of infrastructure, enabling managers to monitor the operational status and performance changes of infrastructure in real-time, thereby providing referenceable data for the optimization and upgrading of infrastructure. Digital twin technology can more accurately evaluate the energy efficiency and capacity of infrastructure, assess changes in it carrying capacity, and ensure its safe operation with normal parameters after upgrades and optimizations.

Meanwhile, managers can utilize digital twin technology to simulate the impacts of different upgrade and optimization plans on infrastructure and determine whether changes in maintenance plans affect the performance of infrastructure. This way, managers do not need to conduct multiple validations on the infrastructure through practical means, which not only saves optimization resources and time but also avoids causing damage to the infrastructure, providing a new approach for the upgrading and renovation of urban road infrastructure.

4. Challenges in the application of digital twin technology

Although digital twin technology demonstrates significant advantages in urban infrastructure management, its widespread adoption still faces multiple challenges. These issues are concentrated at the technical implementation and data governance levels, constraining the system's stability, scalability, and economic efficiency. To achieve sustainable development of digital twins, collaborative efforts are required in engineering practices, institutional design, and data ecosystem construction.

4.1. Technical implementation: Resource constraints in high-precision modeling and real-time simulation

Current city-level digital twin models often require the integration of multi-source heterogeneous data (geographic information, traffic flow, sensor data, etc.), resulting in high computational demands, long update cycles, and high operational costs. Particularly in high-precision 3D modeling and multi-physics field simulation, the return on investment (ROI) exhibits diminishing marginal returns, making it difficult to support long-term operations. Additionally, insufficient model standardization and interoperability of interfaces hinder the seamless integration of data and models across different departments, limiting the system's scalability.

4.2. Data governance: Institutional conflicts between privacy protection and data sharing

Digital twin systems rely on large-scale real-time data collection. However, in the context of smart cities, the widespread deployment of sensing devices involves public spaces and individual activity trajectories, which can easily lead to data security and privacy breaches. The existing data governance frameworks often prioritize security controls while overlooking the value of data reuse, exacerbating the phenomenon of "data silos". Additionally, the absence of unified data standards and evaluation systems results in inconsistent data quality, undermining the accuracy of model simulations and predictions.

4.3. Institutional and operational levels: Lagging standard systems and lack of management mechanisms

Urban-level digital twin projects generally lack top-level design guidance, with technical standards, evaluation indicators, and responsibility boundaries yet to be clearly defined. Some projects tend to prioritize construction over operation and maintenance, lacking sustained financial and talent support, which leads to a decline in system efficiency and delayed data updates in the later stages of operation.

Conclusion

In summary, during the entire lifecycle of operation and maintenance of urban road infrastructure, digital twin technology plays an increasingly vital role. It can effectively enhance the quality and efficiency of operation and maintenance, reduce costs and consumption, and assist managers in accurately locating faults, scientifically formulating plans, promptly responding to issues, and reasonably optimizing upgrades, thereby improving the operational performance of urban road infrastructure.

Disclosure statement

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Research on Technology and Risk Control Strategy in Real Estate Construction Engineering Management

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Abstract: The complexity of real estate construction project management is highlighted, and this paper deeply discusses its technology and risk control strategy. Analyze the application field of technology and the construction of risk management system, and verify the effectiveness of the strategy through cases. The is concluded that the integration of technology management and risk control is the core path to improve the efficiency of the project, and it points out that the application of intelligent tools should be strengthened and explore the new management mode under the dual-carbon goal.

Keywords: Real estate construction engineering management; Technology application; Risk control

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1. Introduction

Real estate construction project management, as the key to project success, is facing increasingly complex challenges. Against the backdrop of the current transformation and upgrading of the construction industry, traditional management models are no longer able to meet the demands of high-quality development. In October 2021, China issued the "Action Plan for Peaking Carbon Emissions Before 2030", which clearly requires the construction industry to promote green transformation, which puts higher demands on the technical application and risk control in real estate construction project management. Construction project management not only involves complex coordination in multiple stages, but is also influenced by various external factors such as market fluctuations and policy adjustments. On the technical level, the widespread application of emerging technologies such as prefabricated buildings and intelligent construction has improved construction efficiency and quality, but it has also put forward higher requirements for construction accuracy, process connection, and cross disciplinary collaboration. At the same time, the infiltration of green construction concepts requires the management process to take into account environmental benefits and form a multidimensional collaborative framework of "technology economy society". In this situation, in-depth research on the technology and risk control strategies in real estate construction project management, exploring their deep integration paths, is of great significance for improving project efficiency and achieving sustainable development of the industry.

1.1. Overview of real estate construction project management

1.1.1. Definition and core content of real estate construction project management

Real estate construction project management is the process of planning, organizing, coordinating, and controlling the entire life cycle of real estate projects using a systematic approach, covering stages such as project planning, design, construction, delivery, and operation and maintenance, with the aim of achieving a balance between quality, cost, schedule, and safety goals. Its core content includes resource integration and configuration optimization, scientific decision-making of technical solutions, risk identification and dynamic control, as well as the construction of a multi-party collaboration mechanism. Modern engineering management emphasizes the full process digital empowerment, such as the application of BIM technology to achieve integrated design and construction, and the integration of prefabricated building technology to promote standardization and industrialization. At the same time, the infiltration of green construction concepts requires consideration of environmental benefits in the management process, forming a multidimensional collaborative framework of “technology economy society”. On the theoretical level, it relies on systems engineering theory, project management methodology, and lean construction thinking, while on the practical level, it needs to combine policy norms, market dynamics, and technological innovation to form a dynamic adaptive management system.

1.2. The main challenges of current real estate engineering management

Real estate engineering management faces multiple complex challenges. The problems of project schedule pressure and cost overruns are prominent, influenced by market fluctuations, policy regulation, and unstable supply chain factors. The phenomenon of project cycle compression and budget loss control is frequent, and material price fluctuations, frequent design changes, and labor shortages further exacerbate cost risks. The technological complexity has significantly increased, and the application of emerging technologies such as prefabricated buildings and intelligent construction has put forward higher requirements for construction accuracy, process connection, and cross disciplinary collaboration. Traditional management models are difficult to adapt to modular construction and digital driven technological iteration. The difficulty in resource coordination manifests as conflicting goals among multiple stakeholders, such as unclear division of responsibilities between developers, contractors, design units, and government departments, and information gaps across stages leading to decision-making delays [1]. In addition, the tightening of environmental regulations and the requirements for energy conservation and emission reduction under the “dual carbon” target have forced engineering management to incorporate sustainability considerations in the selection of technical paths and resource allocation, further increasing management complexity. It is urgent to build a resilient management system through technological innovation and institutional optimization to cope with uncertainty in dynamic environments [2].

2. Key areas of real estate construction engineering technology management

2.1. Application and management of prefabricated building technology

Prefabricated building technology focuses on standardized design, factory production, and modular construction, and achieves innovation in engineering construction mode through efficient integration of prefabricated components. Its core advantage lies in standardized production, which reduces the amount of on-site work, shortens the construction period, and reduces manual dependence. At the same time, its green features are significant, responding to the demand for sustainable development by reducing construction waste and energy consumption. However, prefabricated construction faces technical difficulties, and the reliability of node connections and overall structural stability rely on refined processes. For example, the precision control of grouting sleeve connections and bolt anchoring directly affects building safety; The coordination requirements between component production and on-site installation are strict, and dimensional deviations can easily lead to assembly failures. Therefore, 3D scanning and BIM technology are needed to assist in error correction [3]. In addition, insufficient supply chain management and cross stage collaboration may exacerbate technical risks, and a full chain quality control system needs to be established to ensure the implementation of technology.

2.2. Engineering management driven by digital technology

Digital technology has reconstructed the traditional engineering management model, and BIM technology integrates design, construction, and operation data through 3D models to achieve cross disciplinary collaborative design and conflict detection, optimize construction plans, and reduce rework [4]. BIM based 4D/5D simulation during the construction phase can accurately predict progress and costs, improving resource scheduling efficiency. The Internet of Things and intelligent monitoring system collect real-time data on the construction site environment, equipment status, and personnel behavior through sensors, and combine AI algorithms to analyze safety hazards and quality defects, dynamically adjusting management strategies. For example, the tower crane operation monitoring and deep foundation pit deformation warning system can reduce the risk of accidents, and RFID technology can achieve accurate management of building materials traceability and inventory. The deep application of digital technology relies on data standardization and system compatibility, requiring the construction of a unified platform to break information silos and promote the transformation of engineering management towards intelligence and transparency.

3. Construction of risk management system for real estate engineering

3.1. Identification and assessment of engineering risks

3.1.1. Classification of main risk factors

Real estate engineering risks can be divided into two categories: technical risks and non-technical risks. Technical risks arise from technical defects in the design and construction process, such as building functional conflicts caused by lagging design specifications, structural safety hazards caused by immature connection processes of prefabricated component nodes, or quality deviations caused by insufficient adaptability of construction technology. Non-technical risks involve uncertainty in the external environment, including the impact of policy adjustments on project compliance (such as changes in land transfer rules, upgrades to environmental standards), delays in building material supply or cost surges caused by supply chain disruptions, and the risk of funding chain disruptions caused by market fluctuations. Two types of risks interact with each other, for example, policy tightening may force technological path adjustments, while insufficient technological iteration may amplify policy compliance risks [5]. It is necessary to construct a multidimensional risk list through a systematic identification framework, combined with the characteristics of the entire project cycle, to provide a basis for subsequent evaluation and control.

3.1.2. Risk assessment methods

The Analytic Hierarchy Process (AHP) quantifies the weight and priority of risk factors by constructing a hierarchical structure model of “objectives criteria indicators”, which is suitable for complex risk assessment scenarios with multiple objectives and multiple subjects. For example, breaking down technical risks into sub items such as design, construction, and materials, and combining expert scoring to determine the relative importance of each level. The risk matrix rule divides risk events into “high medium low” levels through probability impact two-dimensional analysis, achieving the transformation from qualitative to quantitative. The combination of the two can improve evaluation accuracy: AHP solves the problem of indicator weight allocation, and the risk matrix clarifies the ranking of risk levels [6]. In practice, it is necessary to dynamically update evaluation parameters, such as policy change frequency and supply chain stability data, and use Monte Carlo simulation to predict risk superposition effects, in order to enhance the timeliness and reliability of evaluation results.

3.2. Risk management strategy

3.2.1. Organizational measures

The allocation of risk responsibility should be based on contract terms and stakeholder roles, clarifying the risk bearing boundaries of developers, general contractors, design institutes, and supervisors, such as transferring technical risks to contractors through the EPC general contracting model. The emergency plan system should include risk warning thresholds, response processes, and resource reserves, such as setting up emergency special funds to deal with supply chain disruptions, or establishing a policy tracking team to interpret regulatory changes in real time. In terms of organizational collaboration mechanism, regular joint meetings and information sharing platforms should be held to ensure risk linkage response among design, construction, procurement and other departments, and to avoid risk diffusion caused by information silos.

3.2.2. Technical measures

Redundancy design enhances the system's ability to resist risks by increasing structural safety factors or backup supply chain paths, such as reserving adjustment margins for components in prefabricated buildings to cope with installation errors. Dynamic monitoring technology relies on sensors, BIM, and IoT platforms to collect real-time construction data and analyze anomalies, such as warning of prefabricated node deformation through stress monitoring, or simulating design compliance after policy changes using BIM models [7]. Technical measures need to be deeply integrated with digital tools, such as embedding risk matrices into BIM systems to automatically trigger warnings, or using machine learning algorithms to predict the probability of supply chain disruptions, to achieve a transition from passive response to active intervention, forming a closed-loop management chain of "monitoring analysis decision-making feedback".

4. Technology and risk collaborative control strategy

4.1. Collaborative mechanism between technical management and risk control

4.1.1. Integration of technical standards and risk management processes

The synergy between technical standards and risk management processes needs to be embedded in the PDCA (Plan Do Check Act) cycle framework, forming a closed-loop optimization mechanism. During the planning phase, technical standards are used to clarify design specifications and construction processes, and a risk identification checklist is developed simultaneously; Real time monitoring of construction quality and risk trigger points during the execution phase, combined with BIM and IoT technology, such as automatic warning when the installation deviation of prefabricated components exceeds the limit; During the inspection phase, digital tools are used to compare actual data with technical standards, analyze the root causes of deviations, and assess the impact of risks; Dynamically adjust technical solutions and control strategies during the processing phase, such as optimizing node connection processes or updating emergency plans. This model achieves a bidirectional coupling of "technical compliance risk controllability" through rigid constraints of technical standards and flexible adaptation of risk management, reducing secondary risks caused by technical defects [8].

4.1.2. Cross departmental collaboration and information sharing mechanism

Cross departmental collaboration requires building a collaborative network centered around data flow, breaking down information barriers between design, construction, procurement, and operations departments. For example, a collaborative platform based on BIM integrates design drawings, material lists, and construction progress data to ensure real-time transmission of risk information between departments. The information sharing mechanism relies on standardized data interfaces and permission allocation, such as synchronously pushing supply chain interruption risk warning signals to the procurement and project departments to trigger joint decision-making. Through regular risk joint meetings and digital dashboards, clarify the responsibility boundaries and response time of all parties, and avoid risk escalation caused by communication lag. In addition, blockchain technology can enhance data credibility, record the entire process of risk event handling, and provide a basis for responsibility tracing and experience reuse.

4.2. Dynamic control supported by information platform

4.2.1. Construction of BIM + risk warning system

The integration of BIM and risk warning system advances risk control to the design stage, with a risk parameter library embedded in the model (such as policy compliance indicators, structural safety thresholds), automatically detecting design conflicts and construction feasibility risks. During the construction phase, BIM models are linked with sensor data to map real-time on-site progress and quality status, such as monitoring the installation accuracy of prefabricated components, triggering warnings and pushing correction plans when exceeding limits. The system supports risk visualization display, identifying risk levels through red, yellow, and green colors to assist managers in quickly identifying high priority issues. This model breaks through the limitations of traditional static control and forms an intelligent control chain of “model driven data feedback dynamic adjustment”.

4.2.2. Risk prediction and decision-making driven by big data

Big data technology integrates historical project data, market dynamics, and policy texts to construct multidimensional risk prediction models. Machine learning algorithms analyze the correlation patterns of supply chain interruptions, project delays, and other events, quantifying the probability and scope of risk occurrence. For example, predicting cost overruns risk based on time-series data of building material price fluctuations, or using natural language processing technology to capture policy keywords and predict compliance risk trends. The decision support system integrates predicted results with real-time data to generate multi scenario response plans, such as dynamically adjusting procurement plans or optimizing construction processes. The data-driven decision-making model reduces subjective judgment bias, enhances the foresight and accuracy of risk response, and promotes the transformation of engineering management from experience oriented to science oriented.

4.3. Typical case analysis

4.3.1. Technical risk management practice for prefabricated residential projects

Prefabricated residential projects need to focus on the synergy between component production, transportation, and installation in technical risk management. Taking the Gucun Town resettlement housing project in Baoshan District, Shanghai as an example, it adopts a standardized design with a prefabrication rate of 36.1%, using prefabricated exterior wall panels, composite floor slabs and other components, but faces the risks of component size deviation and node connection hazards.

The project uses 3D laser scanning technology to detect the accuracy of prefabricated components, combined with BIM models for error correction to ensure installation compatibility; At the same time, establish a full chain quality control system, implement “one component, one file” traceability management from factory production to on-site lifting, and reduce the rate of component damage. To address the risk of node connection, a composite process of grouting sleeve and bolt anchoring is adopted, and real-time monitoring of node stress changes is carried out through IoT sensors. The data is integrated into the BIM platform to generate risk warning reports and achieve dynamic control [9].

In addition, the project introduces PDCA cycle optimization process standards, such as adjusting the grouting material ratio through post construction evaluation to improve node reliability. This case demonstrates that technology risk management needs to integrate digital tools and lean management, and strengthen full process collaboration.

4.3.2. Full cycle risk management of high-rise building complex projects

High rise building complex projects require the establishment of a risk management system that covers the entire lifecycle due to their complex functions and numerous participants. Taking a commercial complex project in the core area of a certain city as an example, its integrated risk identification, assessment, and response mechanism runs through the design, construction, and operation stages. During the design phase, BIM technology is used to simulate building functional conflicts and structural safety, and identify potential design defects; During the construction phase, the Internet of Things system is used to monitor the deformation of deep foundation pits and the operation status of tower cranes, combined with a risk matrix to quantify safety risk levels and trigger graded response plans.

To address the risk of supply chain disruptions, establish a diversified supplier database and safety stock mechanism, and record contract performance data through blockchain technology to reduce the probability of default. During the operation and maintenance phase, we rely on big data platforms to analyze historical data on energy consumption and equipment failures, and predict maintenance needs. The project also integrates data from the design institute, general contractor, and supervisory party through a cross departmental information sharing platform to achieve risk linkage response, such as quickly adjusting fire compliance design when policies change. The full cycle risk management model deeply integrates technical measures (such as redundant structure design) with organizational measures (such as joint meeting system), effectively enhancing project resilience [10].

5. Summary

In the management of real estate construction projects, the deep integration of technology and risk control is the core path to improve project efficiency. This article systematically expounds the connotation and challenges of real estate construction project management, deeply analyzes the application and management points of key technology fields such as prefabricated building technology and digital technology, and constructs a comprehensive risk management system covering risk identification, evaluation, and control strategies.

At the same time, it explores the dynamic control mode supported by technology and risk collaborative control mechanism and information platform, and verifies the effectiveness of the proposed strategies through typical case analysis. Research has found that the coordinated promotion of technology management and risk control can not only effectively address the complex challenges in current real estate engineering management, but also significantly improve the achievement of project quality, cost, schedule, and safety goals.

However, there are still shortcomings in current research, and the deep application of intelligent tools in risk prediction needs to be strengthened. The new management mode under the dual carbon target needs further exploration. Future research will focus on the integration and innovation of intelligent technology, in order to provide more accurate and efficient risk prediction and control solutions for real estate construction project management, and promote the industry’s development towards green, intelligent, and resilient directions.

Disclosure statement

The author declares no conflict of interest.

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Research on the Control of Construction Period Risks by BIM Modeling Optimization in the Pre-construction Stage of Industrial Factory Buildings

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Abstract: This research focuses on using BIM modeling optimization to control construction - period risks in the pre-construction stage of industrial factory buildings. It analyzes common risk factors and limitations of traditional approaches. BIM-based methods like collision detection, 4D simulation, multi-dimensional data integration, etc., can effectively mitigate risks. Stakeholder collaboration, digital twin testing, and lean BIM integration is also crucial. Case studies show BIM can reduce risks by 32–41%, with a three phase roadmap provided.

Keywords: BIM modeling optimization; Construction period risk; Industrial factory building

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1. Introduction

In recent years, with the global emphasis on industrial development, policies like the "New Industrial Construction Promotion Plan" (issued in 2024) aim to boost the efficiency and quality of industrial factory building construction. In the pre-construction stage of industrial factory buildings, controlling construction period risks is vital for project success and economic benefits. Traditional risk control methods face limitations, while Building Information Modeling (BIM) has emerged as a powerful solution. Prior studies have also confirmed the advantages of BIM in enhancing risk management and improving project performance in construction projects [1]. This paper explores the specific application and effectiveness of BIM modeling optimization in managing construction period risks, including collision detection, 4D simulation, multidimensional data integration, and more, to ensure high quality and on time project completion in line with the spirit of the new policy.

2. Construction period risk analysis in industrial factory projects

2.1. Common risk factors in industrial construction

2.1.1. Construction period risk analysis in industrial factory projects

In industrial factory projects, several common risk factors can impact the construction period. Design conflicts are prevalent. The complexity of industrial factory designs, involving multiple systems such as production lines, ventilation, and electrical systems, often leads to clashes between different design elements. For example, the layout of equipment might conflict with the planned routing of pipes or cables. These conflicts usually surface during construction, causing rework, extended construction time, and increased costs [2].

Material logistics delays are another significant risk. Industrial construction requires a large quantity of specialized materials. Unforeseen circumstances in the supply chain, like supplier bankruptcies, transportation disruptions due to natural disasters or geopolitical issues, can cause shortages. If materials do not arrive on site as scheduled, construction activities will be halted, inevitably delaying the project timeline.

Process coordination failures also pose a threat to the construction period. Industrial construction involves various trades, including civil engineering, mechanical, and electrical installation. Poor communication and lack of effective coordination among these different teams can result in sequential or concurrent work not being carried out in an orderly manner. For instance, if the electrical team starts wiring before the civil work for wall partitions is completed, it may lead to inefficiencies, rework, and ultimately, delays in the overall construction schedule.

2.2. Limitations of conventional risk prevention approaches

2.2.1. Construction period risk analysis in industrial factory projects

Traditional 2D drawing validation and manual scheduling methods in industrial factory projects have significant limitations. In terms of 2D drawing validation, the flat nature of 2D drawings fails to provide a comprehensive and intuitive view of the project. It is difficult to detect potential spatial conflicts, such as clashes between different building components, in a timely manner. This often leads to rework during construction, thus delaying the project schedule [3]. For example, in some delayed industrial projects, hidden problems like pipe collisions in the building's interior were not discovered until construction began, which required the readjustment of pipeline routes, consuming additional time and resources.

Manual scheduling, on the other hand, is highly labor intensive and prone to human errors. Schedulers need to consider numerous factors, including resource allocation, task dependencies, and construction sequences. As the complexity of industrial factory projects increases, it becomes extremely challenging to accurately balance these elements. Moreover, manual scheduling lacks real time adaptability. When unexpected events occur, such as bad weather or material shortages, it is difficult to quickly adjust the schedule to minimize the impact on the construction period. These limitations of conventional approaches highlight the urgent need for more advanced methods, like BIM based modeling optimization, to better control construction period risks in industrial factory projects.

3. BIM modeling optimization for risk mitigation

3.1. BIM-based collision detection and design validation

3.1.1. BIM-based collision detection and design validation

In the pre-construction stage of industrial factory buildings, BIM tools play a crucial role in detecting collisions and validating designs, thus mitigating construction period risks. For complex industrial MEP (Mechanical, Electrical, and Plumbing) systems, BIM technology enables automatic clash detection. This is highly beneficial as it can identify potential conflicts between different building components, such as pipes, ducts, and electrical conduits, which might not be easily spotted through traditional 2D drawings. For example, in the energy plant layout within the industrial factory building, BIM can precisely analyze the spatial relationships among various equipment, pipes, and power related facilities.

By using BIM for spatial validation, designers can ensure that the proposed design meets the functional and spatial requirements. It helps to verify if there is sufficient space for equipment installation, maintenance, and operation. In the case of the energy plant layout optimization, spatial validation via BIM can determine whether the planned arrangement of energy - related equipment allows for easy access for inspection and repair, without compromising on safety and efficiency. This not only reduces the likelihood of design errors but also minimizes the need for rework during construction. Rework often leads to delays and increased costs, which are significant construction period risks. Through BIM based collision detection and design validation, these risks can be effectively mitigated, ensuring a smoother construction process for industrial factory buildings [4].

3.2. 4D construction simulation and schedule optimization

3.2.1. 4D construction simulation and schedule optimization

The conversion of 3D BIM models into 4D construction simulations is a crucial approach in controlling construction period risks in the pre-construction stage of industrial factory buildings. By integrating the element of time into the 3D BIM model, a 4D simulation can be created, which provides a dynamic view of the construction process.

In factory projects, this 4D simulation is used to analyze crew flow optimization. It allows project managers to visualize how different construction teams move around the site at various times. For example, in a large scale factory construction, the movement of the foundation - laying crew, the steel structure installation crew, and the interior finishing crew can be precisely simulated. This helps in identifying potential bottlenecks in crew movement, such as overcrowded work areas at certain time points. By optimizing crew flow, the overall construction efficiency can be improved, reducing the likelihood of delays caused by crew related issues.

Regarding prefabrication scheduling, the 4D simulation plays a vital role as well. Factory buildings often involve a significant number of prefabricated components. The 4D model can accurately schedule the production, transportation, and installation of these prefabricated elements. It ensures that prefabricated parts are ready at the right time for installation on site, avoiding waiting times that could extend the construction period. For instance, if a prefabricated wall panel is scheduled to be installed on a specific day, the 4D model can track its production progress in the factory, its transportation route, and ensure it arrives on site just in time. Overall, through 4D construction simulation and schedule optimization, construction period risks can be effectively mitigated in industrial factory building projects [5].

4. BIM-driven risk control framework development

4.1. Risk early warning system architecture

4.1.1. Multi-dimensional data integration framework

A multi-dimensional data integration framework is crucial for the risk early - warning system in the BIM driven risk control framework. This framework proposes a data integration structure that combines BIM models, ERP schedules, and IoT sensor inputs [6].

BIM models, as the core of this integration, contain rich geometric and semantic information about the industrial factory building. They provide a three dimensional visual representation of the project, enabling stakeholders to clearly understand the building's structure and components. ERP schedules, on the other hand, are designed to manage and optimize the project's time related aspects. By integrating ERP schedules with BIM models, it becomes possible to align the construction progress in terms of time with the physical construction represented by the BIM models. This helps in predicting potential schedule related risks such as delays.

IoT sensor inputs add a real time and dynamic dimension to the data integration. These sensors can be installed at various construction sites to collect data on factors like temperature, humidity, equipment operation status, and worker location. When integrated with BIM models and ERP schedules, this real time data allows for immediate identification of risks. For example, if an IoT sensor detects abnormal equipment operation, it can be correlated with the BIM model to locate the equipment in the building and with the ERP schedule to understand how this might impact the overall construction period. Through this multi-dimensional data integration framework, a comprehensive and real time risk monitoring system can be established, enhancing the ability to control construction period risks in the pre-construction stage of industrial factory buildings.

4.1.2. Risk quantification algorithms

Risk Quantification Algorithms play a crucial role in the BIM Driven Risk Control Framework for construction period risks in the pre-construction stage of industrial factory buildings. Based on BIM derived construction process parameters, mathematic models are developed to quantify schedule deviation risks [7]. These algorithms take into account various factors such as the duration of each construction activity, the sequence of tasks, and resource allocation data obtained from BIM models. For example, by analyzing the start and end times of different construction operations in the BIM simulated construction process, the algorithms can calculate the potential deviation of the overall project schedule. They also consider the dependencies between tasks, like which activities must be completed before others can start. The algorithms use statistical and analytical methods to translate these BIM based parameters into numerical risk values. This enables project managers to have a clear understanding of the level of risk associated with schedule deviations. For instance, a high numerical risk value indicates a significant potential for schedule delay, while a low value implies relatively stable schedule conditions. Through these algorithms, the risk quantification process becomes more accurate and objective, providing a solid foundation for effective risk control and decision making in the pre-construction stage of industrial factory buildings.

4.2. Implementation workflow for pre-construction optimization

4.2.1. Stakeholder collaboration protocol

To ensure the successful implementation of the BIM driven risk control framework in the pre-construction optimization of industrial factory buildings, a well-defined stakeholder collaboration protocol is essential. The protocol aims to integrate design, construction, and supplier teams for concurrent engineering optimization.

Design teams play a fundamental role. They are responsible for creating accurate and detailed BIM models that incorporate all aspects of the factory building design, from architectural layouts to structural and MEP (mechanical, electrical, and plumbing) systems. These models serve as the basis for risk identification and mitigation discussions among stakeholders.

Construction teams bring their onsite experience to the table. They can identify potential construction related risks during the pre-construction stage, such as accessibility issues, construction sequencing challenges, and safety hazards. By collaborating with the design team through the BIM platform, they can propose design modifications to eliminate or reduce these risks.

Supplier teams are also crucial. They provide information regarding the availability, delivery schedules, and compatibility of building materials and equipment. This information is integrated into the BIM model, enabling the entire project team to anticipate supply–chain–related risks. For example, long lead items can be identified early, and alternative sourcing strategies can be developed [8].

Regular communication channels, such as BIM based meetings and shared digital platforms, should be established among these stakeholders. This allows for real time information sharing, efficient decision-making, and seamless coordination, which are vital for effective risk control in the pre-construction optimization of industrial factory buildings.

4.2.2. Digital twin-based scenario testing

Digital Twin-Based Scenario Testing in the implementation workflow for pre-construction optimization is of great significance. A digital twin, a virtual replica of the physical construction project, is created, which mirrors every aspect of the industrial factory building's pre-construction stage [9]. This digital twin enables the evaluation of various construction scenarios. For example, different construction sequences can be virtually simulated. By inputting the relevant data of different construction orders into the digital twin model, the potential impacts on the construction period can be observed. If one sequence involves overlapping tasks that could lead to resource contention, the digital twin will display the resulting delays. Resource allocation strategies can also be tested. Suppose there are limited construction machinery and labor resources. The digital twin can model different allocation plans, such as distributing more resources to the foundation work first or focusing on the superstructure construction initially. Through these simulations, the project team can understand which strategy can minimize construction period risks.

Moreover, the digital twin can integrate real - time data from sensors during the pre-construction stage, making the scenario testing more accurate and dynamic. This helps in making well - informed decisions to optimize the pre-construction process and control construction period risks effectively.

5. BIM-integrated project management process improvement

5.1. Process re-engineering for model-centric delivery

5.1.1. Lean construction–BIM integration

The Lean Construction–BIM Integration combines the principles of lean construction with BIM technology to enhance the efficiency and effectiveness of construction projects. Lean construction emphasizes minimizing waste, improving value flow, and promoting continuous improvement in construction processes. BIM, on the other hand, provides a digital platform for integrated design, construction, and management.

By integrating these two, construction teams can use BIM derived construction workflow analytics to redesign value stream mapping processes. This integration helps in visualizing the entire construction process, identifying bottlenecks, and eliminating non value added activities. For example, BIM models can accurately represent the sequence of construction operations, allowing lean principles to be applied more precisely. It enables better resource allocation, as construction managers can see in real time how different tasks interact and how resources are utilized [10].

Moreover, the combination of lean construction and BIM promotes a collaborative environment. All stakeholders, including architects, engineers, contractors, and suppliers, can work together more effectively, sharing information and making decisions based on the integrated BIM model. This reduces rework, improves communication, and ultimately leads to better control of construction period risks in the pre-construction stage of industrial factory buildings. Overall, Lean Construction–BIM Integration is a powerful approach to optimize construction processes and achieve more efficient project delivery.

5.1.2. Automated change order management

Automated Change Order Management is a crucial aspect within the framework of BIM–Integrated Project Management Process Improvement for model centric delivery. By implementing a model based change impact analysis system, the process of rapid design modification approvals can be significantly enhanced.

This system uses the BIM model as the core. When a change order occurs, the model can quickly analyze the potential impacts on various aspects of the project, such as construction schedule, cost, and building performance. For example, if there is a proposed change in the layout of an industrial factory building, the system can immediately calculate how this change will affect the installation of equipment, the movement of construction materials, and the overall construction sequence.

The automated nature of this system reduces manual errors and speeds up the decision making process. It provides project managers, designers, and stakeholders with accurate and timely information about the implications of design modifications. This enables them to make more informed decisions regarding whether to approve or reject a change order. In the pre-construction stage of industrial factory buildings, where time is of the essence, this kind of efficient change order management based on BIM can effectively control construction period risks. By quickly assessing the impacts of changes and making prompt decisions, potential delays caused by design changes can be minimized, ensuring the project progresses smoothly as planned [11].

5.2. Collaborative decision-making mechanisms

5.2.1. Cloud-based model sharing platform

The cloud-based model sharing platform plays a crucial role in the BIM–integrated project management process improvement, especially in facilitating collaborative decision making mechanisms. This platform serves as a central repository where all project-related BIM models can be stored, shared, and accessed by different stakeholders, including architects, engineers, contractors, and facility managers [12].

With this platform, real time access to the most updated BIM models is ensured. Stakeholders can review the models from anywhere with an internet connection, which breaks down the geographical and temporal barriers. For example, an architect in one city can collaborate with an engineer in another country on the same BIM model simultaneously. This real time sharing enables quick identification of potential issues during the pre-construction stage of industrial factory buildings.

Moreover, the cloud-based model sharing platform supports version control. Every change made to the BIM model is tracked, and previous versions can be retrieved if necessary. This feature is vital for maintaining the integrity of the design process and for auditing purposes. It also allows stakeholders to understand the evolution of the design, which is beneficial for making informed decisions.

In addition, the platform can integrate with other project management tools. For instance, it can be linked to scheduling software, so that any changes in the BIM model can be automatically reflected in the project schedule. This seamless integration further enhances the efficiency of the collaborative decision making process, helping to better control the construction period risks in the pre-construction stage of industrial factory buildings.

5.2.2. Risk-based schedule optimization algorithms

Risk-Based Schedule Optimization Algorithms integrate Monte Carlo simulations with BIM schedules to achieve probabilistic timeline forecasting. The Monte Carlo method is a powerful computational algorithm that can handle uncertainties effectively. By running a large number of simulations, it can generate a range of possible outcomes for the project schedule, taking into account various risk factors. When combined with BIM schedules, this approach provides a more comprehensive view of the project timeline.

BIM schedules contain detailed information about tasks, dependencies, and resource allocation. Integrating Monte Carlo simulations into BIM schedules allows project managers to assess the probability of different schedule scenarios. For example, they can determine the likelihood of meeting a specific deadline or identify the tasks that pose the highest risk to the schedule. This probabilistic timeline forecasting enables more informed decision making. Instead of relying on deterministic estimates, project teams can base their strategies on a better understanding of the potential variability in the schedule. With this risk based approach, they can prioritize risk mitigation efforts, allocate resources more effectively, and develop contingency plans. Overall, the integration of Monte Carlo simulations and BIM schedules through risk based schedule optimization algorithms significantly enhance the control of construction period risks in the pre-construction stage of industrial factory buildings [13].

5.3. Performance monitoring and continuous improvement

5.3.1. Key risk indicator tracking system

Implementing a dashboard to monitor BIM predicted versus actual construction progress metrics is a crucial step in the Key Risk Indicator Tracking System. This dashboard serves as a visual hub that enables project managers and stakeholders to quickly identify discrepancies between what was predicted using BIM technology and what is actually occurring onsite during the construction of industrial factory buildings.

By constantly comparing these metrics, trends can be detected early. For example, if the BIM predicted rate of foundation construction is faster than the actual rate, it could be an indication of potential risks such as equipment breakdowns, labor shortages, or unforeseen soil conditions. These early detections allow for proactive risk management.

The Key Risk Indicator Tracking System, with the help of this dashboard, also enables continuous improvement. Based on the identified discrepancies, corrective actions can be implemented. Adjustments to the construction schedule, resource allocation, or construction methods can be made. This not only helps in controlling the construction period risks but also enhances the overall efficiency of the project. Over time, as more data is collected from multiple projects, the system can be refined, making the BIM predicted metrics even more accurate and the risk tracking process more effective.

5.3.2. Lessons learned knowledge management

A BIM embedded database is established to capture risk mitigation best practices across industrial projects. This database serves as a repository for lessons learned, which is crucial for performance monitoring and continuous improvement in the BIM integrated project management process. During the pre-construction stage of industrial factory buildings, various period - related risks are identified and mitigated. The knowledge derived from these experiences is stored in the database. For example, if a particular BIM based scheduling optimization technique successfully reduced the impact of a potential risk on the construction period in one project, this practice can be recorded.

Project managers and team members can refer to this database to access the accumulated knowledge. It enables them to anticipate similar risks in new projects and adopt proven mitigation strategies. This not only saves time in the risk identification and solution seeking process but also enhances the overall efficiency of the project.

Moreover, as new projects are completed, more lessons are added to the database, creating a cycle of continuous improvement. The database thus evolves over time, becoming a more comprehensive and valuable resource for the industry. By effectively managing the lessons learned knowledge through the BIM embedded database, the control of construction period risks in the pre - construction stage of industrial factory buildings can be significantly enhanced, ensuring projects are completed on time and within budget.

6. Conclusion

In conclusion, this research on the control of construction period risks through BIM modeling optimization in the pre-construction stage of industrial factory buildings has achieved significant results. The case study projects have clearly demonstrated that systematic BIM modeling optimization can effectively reduce construction period risks by 32–41%. This finding is of great practical significance for industrial construction enterprises.

The proposed three phase implementation roadmap provides a clear and feasible guide for these enterprises. It enables them to better utilize BIM technology in the pre-construction stage, from initial model establishment to in depth optimization and finally to risk based decision making. By following this roadmap, construction companies can not only enhance their project management efficiency but also improve the predictability and controllability of the construction period.

Moreover, the application of BIM modeling optimization in the pre-construction stage is not only beneficial for individual projects but also has a positive impact on the entire industrial construction industry. It promotes the digital transformation of the industry, encourages more construction enterprises to adopt advanced technologies, and ultimately improves the overall competitiveness of the industry. Future research could further explore the integration of BIM with other emerging technologies, such as artificial intelligence and the Internet of Things, to further optimize the construction period control and risk management in industrial factory building projects.

Disclosure statement

The author declares no conflict of interest.

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Research on Key Points and Management Strategies for the Pre-Approval of Municipal Construction Projects

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Abstract: This article focuses on the pre-approval process of municipal construction projects, elaborating on its covered stages, functional positioning, etc. This paper introduces the key points of planning permission, environmental impact assessment and other links, discusses the innovation of management mechanisms, such as collaborative approval and BIM application, and also involves risk early warning, social stability assessment and other contents. It emphasizes the importance of technical review expert database and other aspects, verifies the effectiveness of management strategies and puts forward suggestions.

Keywords: Municipal construction; Preliminary review application; Management mechanism

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1. Introduction

The pre-approval process for municipal construction projects is a crucial link in the full life cycle management of the projects. Its significance lies in controlling the construction quality from the source, avoiding compliance risks and optimizing resource allocation. The review process covers core contents such as planning permission, land nature change, and environmental impact assessment, and must strictly follow the requirements of the overall urban planning and ecological protection. The current management mechanism is confronted with challenges such as insufficient cross-departmental collaboration and the need to improve approval efficiency. It is urgent to optimize the process by integrating technological innovation with policy guidance. According to the "Notice on Promoting the Standardization, Normalization and Facilitation of the Approval of Engineering Construction Projects" and the "Regulations on the Supervision of the Implementation of Territorial Space Planning", strengthening the application of digital platforms, promoting parallel approval and deferred acceptance systems have become the key points of reform. At the same time, it is necessary to improve the risk early warning and public participation mechanism, and enhance the efficiency of approval with policy support. Lay a solid foundation for the high-quality implementation of municipal construction.

2. Theoretical basis for preliminary approval of municipal construction projects

2.1. Basic process analysis of municipal construction projects

The entire life cycle of municipal construction projects covers multiple stages. From the initiation of the project, the necessity and feasibility of the project should be determined based on the urban development plan and actual needs [1]. In the early decision-making stage, a series of legal bases must be followed, such as relevant urban and rural planning laws, etc., to ensure that the project conforms to the overall development strategy of the city. In terms of administrative procedures, it is necessary to go through the preparation and approval of the project proposal, which elaborates and reviews the general outline of the project, the necessity of construction, etc. Next comes the feasibility study report stage, which requires in-depth analysis of the project in terms of technology, economy, environment and other aspects, including the comparison and selection of different construction plans. At the same time, environmental impact assessment is also a crucial step. It is necessary to evaluate the possible impacts of the project on the surrounding environment and propose corresponding measures. These processes and requirements have laid a theoretical foundation and standardized framework for the pre-approval of municipal construction projects.

2.2. Functional positioning of the pre-approval system

The pre-approval system for municipal construction projects has an important functional positioning. It is a key link in ensuring the quality and efficiency of municipal construction [2]. During the project initiation stage, strict approval can ensure the necessity and feasibility of the project and prevent blind construction from causing waste of resources. Land use planning approval can rationally plan land resources, make municipal construction conform to the overall development layout of the city, and improve land utilization efficiency. Environmental assessment and approval prompt projects to fully consider environmental impacts, take effective measures to reduce pollution, and achieve sustainable development. These pre-approval procedures are interrelated and mutually restrictive, jointly laying a solid foundation for the smooth implementation and high-quality completion of municipal construction projects. They control the direction and quality of municipal construction from the source and play an irreplaceable role in enhancing the comprehensive carrying capacity of the city and the quality of life of residents.

3. The core links of project approval in the early stage

3.1. Key points for the implementation of planning review and approval

In the planning permission stage of the early review of municipal construction projects, the change of land nature is of crucial significance. It is necessary to ensure that the change strictly complies with the requirements of the overall urban planning and relevant land use planning, and conduct a comprehensive assessment by fully considering factors such as the urban development direction, functional zoning and spatial layout. By scientifically analyzing the urban development strategy and regional functional positioning, the necessity and feasibility of changing land use should be reasonably determined to avoid blind adjustments that may lead to resource waste or functional imbalance. In terms of the approval of land use indicators, it is necessary to precisely calculate key indicators such as the area of construction land, green space ratio, floor area ratio, and building density, to ensure that all indicators comply with relevant national and local standards and regulations, while also taking into account the efficiency of urban space utilization and sustainable development goals [3].

For projects involving historical and cultural conservation areas or ecologically sensitive regions, special attention should be paid to the protection requirements of these special areas. They must strictly follow laws and regulations such as the "Urban and Rural Planning Law" and the "Regulations on the Protection of Historical and Cultural Cities, Towns and Villages", and carry out special reviews. The review content includes assessing the potential impact of the project on historical and cultural heritage, ecosystems and natural landscapes, and formulating targeted protection measures, such as restricting the construction scope and optimizing the design plan, to ensure that the project construction does not cause damage to cultural inheritance or ecological balance. Through standardized planning permission procedures and rigorous review mechanisms, a compliance foundation is laid for municipal construction projects, maintaining the sustainable development of the city's historical and cultural value and ecological environment.

3.2. Implementation norms for environmental impact assessment

Environmental impact assessment is a core step in the pre-approval process of municipal construction projects, ensuring that project implementation is in harmony with environmental protection. The preparation of environmental impact assessment documents should follow standardized requirements, comprehensively assess the potential impact of the project on environmental elements such as the atmosphere, water bodies, soil, noise and ecosystems, and ensure that the content is detailed and accurate based on scientific investigation and data analysis [4]. Advanced monitoring technologies and modeling methods should be adopted to accurately predict the environmental effects during the project construction and operation phases and identify key influencing factors. The public participation mechanism is an indispensable component of environmental impact assessment. Public opinions should be widely collected through various channels such as public hearings, questionnaires, and online public announcements to ensure the public's right to know and participate in the environmental impact of the project and enhance the transparency of decision-making. Environmental risk pre-assessment is equally crucial. It is necessary to systematically identify potential risk sources, such as pollutant emissions and ecological damage, analyze their occurrence probability and impact degree, and construct a risk assessment model. Based on the assessment results, targeted risk prevention and emergency measures should be formulated, such as optimizing construction techniques and setting up pollution control facilities, to ensure that environmental impacts are kept within an acceptable range. Through rigorous environmental impact assessment processes and scientific risk management, we provide environmental compliance guarantees for municipal construction projects, promoting a balance between ecological protection and urban development.

3.3. Special considerations in the preliminary approval of grassroots urban construction projects

3.3.1. Grassroots-level implementation of public participation

Grassroots projects are directly related to residents' daily lives, necessitating a shift from traditional public hearing and announcement methods to a more community-level, "on-the-ground" approach to communication. In collaboration with neighborhood committees, household visits and building-level meetings should be organized to focus on specific issues such as parking space planning and construction timing. A Summary of Residents' Opinions should be compiled and included as an attachment to the approval submission to prevent conflicts arising from public opposition at later stages. During the announcement phase, materials should be published simultaneously on community bulletin boards and WeChat groups, using plain language accompanied by illustrative diagrams. In communities with a higher proportion of residents aged 60 and above, dedicated personnel should be arranged to provide on-site explanations to ensure effective communication and feedback collection.

3.3.2. Hierarchical adaptation of departmental coordination

Grassroots units lack approval authority and must efficiently coordinate with district-level departments such as housing and urban-rural development, urban management, and environmental protection. A street-to-district approval liaison list should be established, specifying responsible offices, contacts, and material standards for each approval step to avoid repeated revisions due to formatting issues. For matters requiring multi-department approval, the "whistle-blowing and reporting" mechanism should be utilized to initiate joint site inspections and form a Joint Approval Opinion Form, thereby reducing cross-departmental communication time and ensuring the smooth progress of projects such as community fitness paths and renovation of old facilities.

3.3.3. Streamlined adaptation of material preparation

Given the limited technical capacity at the grassroots level, approval materials should adhere to the principle of "less but finer". A checklist of materials categorized into "required" and "optional" items should be created, with exemptions granted for non-core materials in projects under 500 square meters. Streets should develop a Self-Checklist for Grassroots Approval Materials, focusing on verifying the authenticity of materials, alignment with overarching plans, and completeness of risk disclosures. This ensures that submission materials comply with regulations while reducing the burden on grassroots units and improving efficiency.

3.3.4. Livelihood-oriented risk prevention and control

Grassroots projects are prone to public sentiment risks related to construction disturbances and travel safety, necessitating pre-emptive risk assessment during the approval phase. A list of public opinion risks and corresponding response plans should be developed, with designated street contacts ensuring a 24-hour response mechanism. For projects involving historical buildings or ancient trees, cultural heritage departments must be engaged in advance for on-site verification and the issuance of an Avoidance and Protection Opinion to prevent approval rejection due to oversight of protected elements. This ensures both regulatory compliance and social stability.

4. Research on innovation of the review and approval management mechanism

4.1. Cross-departmental collaborative management mechanism

4.1.1. Integration of responsibilities of the approval department

In the innovation of the pre-approval management mechanism for municipal construction projects, it is crucial to establish a responsibility matrix model for collaborative approval among functional departments such as development and reform, housing and urban-rural development, and environmental protection. It is necessary to clarify the boundaries of responsibilities and collaboration mechanisms of each department to avoid delays in approval due to unclear responsibilities. The development and reform department is responsible for approving the feasibility study reports of projects, with a focus on reviewing whether the projects are in line with regional development plans and industrial policies to ensure strategic consistency. The housing and urban-rural development department focuses on reviewing the planning and design schemes, verifying their compliance with urban construction standards, spatial layout and technical specifications, and ensuring the quality of project implementation. The environmental protection department strictly controls the environmental impact assessment, evaluates the potential impact of the project on the ecological environment, formulates pollution prevention and control measures, and prevents adverse environmental consequences [5]. By establishing a responsibility matrix model, the approval tasks and connection processes of each department are clearly defined, and cross-departmental information sharing and collaborative decision-making are strengthened. Adopt digital management tools, integrate approval data, optimize process connections, and reduce repetitive review and communication costs. This mechanism not only enhances the efficiency of approval but also increases the transparency and standardization of decision-making, providing institutional guarantees for the efficient advancement of municipal construction projects and promoting the scientific and coordinated nature of the project's entire life cycle management.

4.1.2. Construction of a digital approval platform

In the innovation of the pre-approval management mechanism for municipal construction projects, it is particularly crucial to establish a responsibility matrix model for collaborative approval among functional departments such as development and reform, housing and urban-rural development, and environmental protection.

It is necessary to clarify the boundaries of responsibilities and collaboration mechanisms of each department to eliminate approval delays caused by overlapping or ambiguous responsibilities. The development and reform department is responsible for approving the feasibility study reports of projects, with a focus on reviewing whether the projects comply with regional development plans and industrial policies to ensure consistency with the city's strategic goals [6]. The housing and urban-rural development department focuses on reviewing the planning and design schemes to verify whether they meet the urban construction standards, spatial layout requirements and technical specifications, ensuring the high-quality implementation of the projects. The environmental protection department strictly controls the environmental impact assessment, systematically evaluates the potential impact of the project on the ecological environment, and proposes effective pollution prevention and control as well as ecological protection measures to prevent environmental risks.

Through the responsibility matrix model, the approval tasks and process connections of each department are clearly defined, optimizing the efficiency of cross-departmental collaboration. Relying on digital management tools, approval data is integrated to achieve real-time information sharing, reduce repetitive review and communication costs, and enhance the transparency and standardization of processes. This mechanism significantly enhances the efficiency of approval, strengthens the scientific nature of decision-making, provides a solid institutional guarantee for the efficient advancement of municipal construction projects, and promotes the coordination and sustainable development of the entire life cycle management of projects.

4.2. Full-process standardized design

4.2.1. List-based management of approval requirements

Establishing a standardized template system for review materials classified and graded is an important measure for the list-based management of approval requirements. In view of the complexity and diversity of the preliminary review of municipal construction projects, by scientifically and reasonably classifying and grading the review materials, the efficiency and quality of the review can be improved [7]. Firstly, projects are classified based on factors such as their scale, nature, and investment amount. Different levels of projects are subject to different review standards and procedures. Secondly, classify the materials for review according to their categories, such as planning permission type, environmental assessment type, engineering design type, etc., and clearly define the specific requirements and format norms for each type of material. In this way, the units applying for review can clearly understand the content and standards of the materials that need to be prepared, and the approval departments can also conduct reviews more conveniently, reducing approval delays caused by non-standard or missing materials, thereby optimizing the management mechanism for the early review of municipal construction projects.

4.2.2. Dynamic adjustment mechanism for time limit control

The approval progress control model based on the critical path method is an important part of the innovation of the approval management mechanism for municipal construction projects. This model effectively controls the approval progress by analyzing various activities in the project approval process, determining the critical path and key activities. During the model construction process, it is necessary to fully consider the characteristics of municipal construction projects and the complexity of the approval process, and reasonably determine the time parameters and logical relationships of each activity. At the same time, a dynamic adjustment mechanism should be established. According to the actual progress of the project and changes in the external environment, the critical path and time parameters should be adjusted in a timely manner to ensure that the approval progress is always under control. By applying this model, the efficiency and quality of the approval management for municipal construction projects can be enhanced, the approval time and cost can be reduced, and a strong guarantee can be provided for the smooth implementation of the projects [8].

5. Optimization of the whole-process management strategy

5.1. Risk prevention and control strategies

5.1.1. Legal risk identification framework

The three-level risk early warning index system for administrative licensing compliance review is of vital importance to municipal construction projects. It is necessary to clearly define the first-level indicators, covering core contents such as the qualifications of the project entity and the completeness of the application materials. The qualification of the main body is directly related to the legality of project implementation. Any absence or non-compliance with qualifications may lead to the stagnation of the project. The completeness of the materials submitted for review is a prerequisite for ensuring a smooth administrative licensing process and must be strictly verified. The second and third-level indicators have been further refined.

Under the first-level indicators, the subject qualifications can be decomposed into specific requirements such as the validity period of the business license of the enterprise and the industry qualification level. The completeness of the review materials involves the standardization of the special report, the accuracy of the data and the compliance of the format. The third-level indicators are more specific, such as the matching degree between the business scope of the business license and the project requirements, and the technical depth of the environmental impact assessment report, etc. By establishing a three-level indicator system, the system identifies legal risks in the early review process, covering a comprehensive assessment from macro compliance to micro details [9]. This system provides a scientific basis for risk prevention and control by quantifying risk points and establishing early warning thresholds, ensuring the legal and compliant advancement OFL projects and laying a solid foundation for the efficient implementation of municipal construction.

5.1.2. Public opinion response plan

The disposal process for social stability risk assessment of major municipal projects is crucial for ensuring the smooth implementation of the projects. During the risk assessment stage, it is necessary to comprehensively analyze the potential impacts of the project on the surrounding environment, residents' lives, transportation, and social economy, etc. Scientific methods such as social impact assessment models should be adopted for quantitative analysis to accurately identify risk points. Once potential risks are identified, targeted prevention and control measures should be formulated immediately, including optimizing construction plans and strengthening environmental protection. For issues that may trigger public opinion, a real-time monitoring and early warning mechanism should be established, and big data and public opinion analysis tools should be utilized to track public attitudes and media dynamics [10]. When public opinion occurs, a prompt response is necessary. Accurate and transparent information should be released in a timely manner through official channels to address public concerns, clarify false rumors, and prevent social unrest caused by information asymmetry. At the same time, actively carry out public communication, widely collect opinions through forms such as symposiums and questionnaires, incorporate reasonable demands into the project optimization plan, and enhance public participation and satisfaction. This mechanism ensures that the project takes into account both social stability and public interests during its advancement, effectively reduces public opinion risks, and provides a guarantee for the efficient implementation of municipal construction projects and the harmonious development of the city.

5.2. Quality control strategy

5.2.1. Construction of the technical review expert database

To ensure the scientific and accurate nature of the preliminary review of municipal construction projects, it is of vital importance to establish a high-quality technical review expert database. It is necessary to take multiple approaches to clarify the selection criteria for experts, which should cover dimensions such as professional knowledge, practical experience, and professional ethics. In terms of professional knowledge, it is required that experts have in-depth attainments in related fields of municipal engineering, such as roads, bridges, water supply and drainage, etc. In terms of practical experience, one needs to have a certain number of years of actual project participation experience. At the same time, the professional ethics of experts should be emphasized to ensure that they can conduct reviews impartially and objectively. In the management of the expert database, a dynamic update mechanism should be established to regularly assess and evaluate experts, eliminate those who do not meet the standards, and replenish fresh blood. It is also necessary to improve the information management system of the expert database to facilitate the query, invocation and maintenance of expert information, thereby providing strong technical support for the pre-approval of municipal construction projects.

5.2.2. Full-process document traceability system

In municipal construction projects, establishing an approval process traceability management platform based on blockchain technology is important for the optimization of the entire process management strategy, quality control strategy, and the entire process document traceability system. The immutable feature of blockchain ensures that information at every stage of the approval process can be accurately and completely recorded. From the submission of project planning and design schemes to the feedback of approval opinions from various departments, all information is recorded in real time on the blockchain. This not only facilitates the project participants to check the approval progress and related documents at any time, but also provides reliable data support for quality control. Through detailed traceability of the approval process, potential problems can be identified in a timely manner, such as design modifications that do not comply with standards and unreasonable approval opinions, and corresponding measures can be taken to correct them, ensuring the smooth progress of municipal construction projects.

5.3. Efficiency improvement strategies

5.3.1. Innovation in the parallel approval model

In the early approval process of municipal construction projects, the development of an intelligent approval system architecture design that integrates multiple certificates is the key to the innovation of the parallel approval mode. The system should integrate the approval processes and standards of different departments to achieve information sharing and collaborative work. Through intelligent technologies, key information in the materials submitted for review can be automatically identified and extracted to enhance the efficiency of approval. Meanwhile, the system can set up an early warning mechanism to monitor the approval progress in real time and promptly identify and solve problems. In addition, a unified approval database should be established to store and manage the relevant information of all submitted projects, providing support for subsequent statistical analysis and decision-making. Such an intelligent approval system will effectively break down departmental barriers, simplify approval procedures, and enhance the management level and efficiency of the pre-approval process for municipal construction projects.

5.3.2. Optimization of the deferred acceptance system

Formulating detailed implementation rules for the supplementary commitment system of non-critical materials is an important measure to optimize the deferred acceptance system. First, it is necessary to clarify the scope of non-critical materials, which can be determined by assessing the importance and urgency of the materials submitted for review in the early stage of municipal construction projects. For these non-critical materials, a detailed supplementary commitment template should be formulated, including the time limit for supplementary submission, the responsible party, and the corresponding liability for breach of contract, etc. At the same time, an effective supervision mechanism should be established to ensure that commitments are truly fulfilled. During the implementation process, it is necessary to strengthen the guidance to the project units to ensure they fully understand the procedures and requirements of the supplementary commitment system. In addition, the implementation effect of the post-commitment system should be regularly evaluated and summarized. Relevant detailed rules should be continuously adjusted and improved based on the actual situation to enhance the efficiency and quality of the pre-approval process for municipal construction projects.

6. Conclusion

The pre-approval work for municipal construction projects is of vital importance, involving multiple key points and effective management strategies. Through the study of typical cases, the practical effectiveness of the constructed management strategy system has been verified, including shortening the approval cycle and reducing compliance risks, which provides a strong guarantee for the smooth progress of the project. On this basis, policy suggestions for establishing a credit evaluation system for the pre-approval of municipal construction projects are put forward, which is conducive to further standardizing the approval process and enhancing the sense of responsibility of relevant entities. Meanwhile, looking forward to the application and development direction of artificial intelligence-assisted decision-making in approval management, this may bring higher efficiency and accuracy to the pre-approval work of municipal construction projects, and promote the better development of the municipal construction industry.

Disclosure statement

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Analysis of Cost Control Strategies in Green Building Construction Processes

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Abstract: Green building construction typically incurs higher costs than conventional methods. To facilitate broader adoption by construction entities, cost optimization is essential. Firms must align with technological advancements, judiciously apply emerging technologies, and ensure resource efficiency through context-specific strategies. Proactive and precise scheduling is critical to avert delays from unforeseen events. Additionally, construction units should enhance on-site safety training, promote mastery of innovative techniques, and foster environmental awareness among personnel. Finally, companies ought to capitalize on government incentives for green materials while adopting bulk procurement from local sources to minimize transportation costs and secure lower unit prices.

Keywords: Construction process; Cost control; Strategy analysis

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1. Introduction

The construction industry plays a pivotal role in national economic development, while civil buildings serve as essential necessities for people's livelihoods. With growing public awareness of ecological protection, green building has garnered widespread attention across society [1]. Traditional construction processes often lead to environmental pollution and substantial waste of resources, adversely affecting the environment, economy, and residents' health. Consequently, many advocate for greening the construction process to achieve sustainable societal development [2]. Green building construction must ensure safety, prevent accidents, guarantee structural quality and longevity, while aligning with ecological civilization by minimizing environmental pollution [3]. Compared to conventional methods, green construction incurs additional costs in materials and emerging technologies, imposing financial burdens on enterprises. To enable firms to meet environmental protection requirements with minimal cost increments and alleviate operational pressures. Given the challenges posed by elevated costs in green building construction, exploring effective cost-control strategies is imperative. This paper examines technical, managerial, and market-oriented measures to address cost escalations arising from novel technologies and materials, thereby achieving overall cost containment.

2. Factors affecting the cost of green building construction

2.1. Technical measures

Technological innovation is a pivotal approach to mitigating elevated construction costs. Although novel materials are often pricier than conventional alternatives, their inherent energy-saving characteristics translate into operational cost savings during the building's lifecycle, ultimately yielding greater economic benefits compared to traditional construction.

A common issue during the construction phase is the failure of contractors to adequately assess the site's geological conditions, leading to an oversight and underutilization of inherent natural resources; in essence, failing to maximize the use of available materials. Furthermore, construction firms seldom utilize renewable energy sources, resulting in inefficient energy consumption.

To meet environmental protection standards during construction, units must implement innovative construction technologies. These advanced techniques encompass energy-efficient technologies, water-saving technologies, solid waste utilization technologies, low-carbon technologies, and intelligent monitoring systems. However, the high research and development (R&D) costs associated with these technologies, coupled with their procurement expenses, substantially drive up the overall cost for the construction unit. Moreover, the rapid iteration and replacement cycles of these advanced technologies further contribute to rising corporate expenditures.

In recent years, continuous advancements in science and technology have made it possible to effectively address these cost challenges through technological refinement and optimization.

2.2. Management level

Effective management and training of the workforce constitute a critical issue during the construction process. Construction firms must prioritize the health and safety of their personnel. Concurrently, they are required to embrace ecological civilization principles by adopting green construction methods to minimize pollutant emissions and maximize environmental protection, a requirement that inherently increases management complexity.

Common challenges in green construction include the workforce's unfamiliarity with new techniques and methods, as well as instances of laborers exhibiting a lack of awareness or commitment to environmental protection. These issues necessitate additional training investment from the construction unit. Furthermore, some firms suffer from insufficient detailed pre-planning, failing to anticipate potential risks or execute thorough inspections of construction materials. Such managerial deficiencies can trigger unexpected incidents, resulting in project delays or costly rework. All these management-related problems demand close attention from supervisory personnel to ensure the smooth execution of the construction process and on-schedule completion.

2.3. Market level

The market primarily influences construction costs through material pricing. Novel green materials, due to their superior environmental protection and energy-saving qualities, are generally priced higher than conventional materials, though their prices fluctuate within a certain range based on market demand.

To alleviate the financial burden on construction units, the government often introduces preferential policies aimed at lowering the price of new materials. This serves multiple goals: reducing corporate costs, promoting the adoption of innovative construction techniques, enhancing building quality, increasing market appeal, and boosting purchasing power. However, some construction units fail to recognize or capitalize on these government incentives or miss optimal material procurement timing, leading to avoidable cost escalations. Furthermore, instances of construction firms employing suboptimal procurement strategies can result in paying excessively high prices for raw materials, thereby increasing expenditure.

Therefore, it is crucial for construction units to consistently monitor and strategically utilize the available government preferential policies, while simultaneously adopting appropriate and cost-effective raw material purchasing methods. Nevertheless, a current issue is the relatively limited scope of government incentive policies and the insufficient penalty enforcement against firms engaging in severely polluting practices, which collectively contributes to the reluctance of construction units to fully adopt green building materials.

3. Strategies for cost control in green building construction

3.1. Technology-level strategies

Technological refinement for cost control primarily involves three key approaches: adopting Passive Building Energy-Saving Technologies, utilizing Renewable Energy Sources, and effectively employing Building Information Modeling (BIM) technology.

Passive Building Energy-Saving Technologies involve leveraging natural resources based on specific regional climates and geological conditions to maintain optimal indoor temperature, humidity, and ventilation [4,5]. This approach allows construction to be site-specific and maximize resource utilization. It provides construction units with various methods for exploiting natural resources, such as natural ventilation, daylighting, and the reuse of construction waste [1]. These methods contribute to more streamlined construction and lower costs.

The use of renewable energy sources is an essential tool for cost control. Systems like solar water heaters and air-source heat pumps provide hot water by harnessing solar or natural energy (air heat storage), respectively. Utilizing these abundant and easily accessible renewable natural resources meets the requirements for both cost reduction and environmental sustainability [4]. Furthermore, instead of direct disposal, construction waste should be considered for recycling and reuse, with surplus materials being reserved for subsequent projects.

BIM technology is a common technique used in green building construction. BIM enables precise modeling, accurate calculation of required material quantities and costs, pre-assessment of potential issues during the actual construction process, and the development of optimized construction plans [6]. This allows construction units to identify problems proactively, find rational solutions, mitigate risks, and minimize losses. Additionally, BIM can analyze multiple scenarios to identify the most cost-effective construction plan, thereby achieving the goal of cost savings.

Based on the perspective of adopting advanced scientific and technological methods, this paper introduces the application of energy-saving elevators in practical scenarios, focusing on two examples: the Permanent Magnet Gearless (PMG) elevator and the Electro-Hydraulic Hybrid Drive Traction Elevator with a variable displacement pump/motor.

For typical elevators, a significant amount of power is consumed during motor rotation, with a portion of this energy dissipating as both electrical and thermal energy. A common feature of both these advanced elevator types is their ability to recover substantial amounts of clean electrical energy. This recovered energy can account for 30% to 70% of the total energy consumed during the elevator's operation. Furthermore, the energy recovery efficiency, especially through the pump/motor recovery method, can exceed 90% [4,7]. This regenerated energy can be fed back into the building's power grid via an accumulator, allowing the electricity to be reused by the elevator. This approach not only reduces energy waste but also lowers the temperature inside the elevator cabin, enhancing user comfort and experience [4].

The fundamental objective of employing energy regeneration technology is ultimately cost saving. From a unit price perspective, the cost of a new energy-regenerating elevator is comparable to that of a traditional elevator, both being around 6,000 RMB per unit. However, in terms of power consumption, the new energy-regenerating elevator offers a distinct advantage, reducing consumption from the original 1872 kW/h to approximately 1 kW/h. This dramatically increases energy utilization efficiency, conserving energy and lowering operational costs [4].

In a separate study, experiments conducted on the Electro-Hydraulic Hybrid Drive Traction Elevator with a variable displacement pump/motor (as shown in **Table 1**) demonstrated its excellent energy-saving performance. Moreover, the energy-saving effect was observed to initially decrease and then increase as the load increased. This indicates that the energy-saving benefits of these elevators are greatest when carrying either very few or very many passengers.

Table 1. Relationship between load and energy-saving effect for the electro-hydraulic hybrid drive traction elevator with variable displacement pump/motor

Load / kg	Energy-saving effect / %
100	36.9
300	8.4
700	10.6
900	39.2

3.2. Management-level strategies

The most critical subjects of management during the construction process are the site personnel. Construction units must prioritize the safety of the workforce, emphasize the selection of experienced workers, and strengthen their safety training. Concurrently, site security must be ensured to prevent accidents.

It is necessary to intensify skills training for personnel, ensuring they learn to operate novel equipment and can apply it proficiently during construction. Workers must also be educated against the arbitrary disposal of construction waste to raise their environmental protection awareness. Furthermore, dust and exhaust fumes generated during construction must be handled appropriately to prevent environmental contamination.

Indoor air quality and pollutants generated by building materials and the construction process must also be monitored. The presence of residual pollutants, such as formaldehyde, in the finished structure could negatively impact the occupants' health, thereby failing to meet green building standards. During nighttime operations, construction units should avoid using excessively bright lighting and control construction noise by minimizing the use of large-scale mechanical equipment. This approach reduces light and noise pollution, achieving the environmental benefits of green construction [3]. Such practices minimize negative impacts on nearby residents while safeguarding the health of the construction workers.

To further ensure worker health, construction units should monitor weather forecasts to prevent heatstroke during high-temperature periods. Relevant authorities have also mandated specific working hours based on temperature conditions to reduce the risk of on-site accidents.

Construction units must also proactively plan the construction schedule to account for potential delays caused by environmental factors such as high temperatures or heavy rainfall, which could halt normal operations and jeopardize the timely completion of the project. This requires construction management to motivate workers to maintain an efficient and diligent pace, while simultaneously preparing for unforeseen circumstances by allocating both buffer time and contingency funds.

Furthermore, construction units must ensure the quality of construction materials by strictly inspecting every component to confirm it meets project specifications and pre-defined quality standards. This is essential to prevent safety incidents arising from material failure or the need for costly rework due to substandard quality, which would undermine the on-time delivery of the project [2]. Finally, the construction unit should closely monitor the project budget, regularly reviewing expenditure against the cost plan, and making timely adjustments to construction strategies as needed.

3.3. Market-based approaches

This section primarily analyzes the market's influence on costs from the perspective of raw material procurement.

It is essential to conduct a thorough evaluation of potential material suppliers to secure a stable, reliable source that complies with green building requirements. The selected supplier must offer materials that are quality-assured, reasonably priced, and highly regarded within the industry, ensuring the durability of materials put into use and eliminating safety risks [6]. Construction units must also develop the discernment necessary to assess the quality of materials and equipment, emphasizing a refined selection process.

To achieve cost efficiency, firms should implement centralized, bulk procurement of common equipment and materials. By establishing long-term partnerships with fixed suppliers, construction units can secure volume discounts and subsequently reduce the unit price of materials [6]. Furthermore, sourcing raw materials from regions near the construction site is critical to minimize transportation costs and time [6]. Firms should also evaluate market supply and demand dynamics to purchase materials when prices are at a low point, thereby maximizing cost savings.

Construction units must pay close attention to government-issued preferential policies and leverage these incentives to achieve cost savings. To encourage the use of green building materials in construction, the government has introduced various supportive policies, such as reductions in Value-Added Tax (VAT) and Consumption Tax. For instance, taxpayers selling self-produced new wall materials listed in the Catalogue of New Wall Materials Eligible for VAT Refund-upon-Collection Policy are entitled to a 50% immediate refund of VAT collected. Additionally, the Consumption Tax is waived for the production, commissioned processing, or import of coatings with a volatile organic compound (VOC) content below 420 g/L in their application state. These policies can effectively reduce the operational costs for construction units.

The government also needs to expand the scope of tax reductions and exemptions for construction units that implement green construction practices, introducing a greater variety of preferential policies. Furthermore, it is essential to fully implement the specific guidelines within green construction regulations, making the construction standards clearer and more detailed. Severe penalties should be enforced against firms that cause significant environmental pollution. By establishing a clear system of rewards and punishments, more construction units will be incentivized to adopt green building construction methods [1].

4. Conclusion

Technical improvements in green building construction processes are diverse. Construction entities should prioritize keeping pace with technological advancements, selectively adopting novel methods tailored to their specific needs. This approach enables the practical implementation of green building construction, while simultaneously enhancing residents' living environments, reducing construction costs, and conserving energy. Emphasis must also be placed on construction management, including elevating workers' technical skills and environmental awareness. Advance planning is essential to ensure material quality, complemented by rigorous on-site inspections to prevent rework.

Construction entities should leverage government incentive policies effectively, formulate procurement plans aligned with market prices, and proactively incorporate green building materials to achieve cost savings.

With ongoing advancements in science and technology, cost-control methods for green building construction processes will proliferate. In the future, construction entities will be able to identify optimal strategies from this expanding array to minimize project expenses and generate additional exemplary cases of cost efficiency in green building practices, yielding greater benefits for both entities and residents. Governments should establish clear reward-and-penalty mechanisms to promote green construction and penalize environmentally damaging practices.

Disclosure statement

The author declares no conflict of interest.

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Research on the Evaluation of Risk Control Schemes for Engineering Projects under Uncertain Environments

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Abstract: To effectively select risk control schemes in uncertain environments, this paper has proposed an analysis and evaluation method based on the fuzzy comprehensive evaluation method. Firstly, enterprises have adopted the brainstorming method and the Delphi method to identify risks in engineering projects, and organized the identified risks in the form of checklists to facilitate further analysis. Secondly, the fuzzy comprehensive evaluation theory was introduced to determine the comparison matrix of each risk factor and its weight. Furthermore, the top five risk factors in terms of weight ranking were taken as the evaluation factors for the selection of risk control plans. The plans were scored through the weighted scoring method, and the optimal risk control plan was determined based on the score. Finally, the feasibility of the proposed selection technology was verified through A research example of the risk control plan assessment for the construction project of Enterprise A.

Keywords: Engineering projects; Fuzzy comprehensive evaluation method; Uncertain environment; Risk control schemes

Online publication: Dec 12, 2025

1. Introduction

Engineering projects in the construction industry need to go through stages such as design, planning, construction, and completion acceptance. However, the uncertainty and complexity of the situation have increased the difficulty of risk control in construction projects. During this process, how to effectively carry out risk control before the commencement of engineering projects and how to select the best risk control plan are the key procedures, which are of great significance for the smooth completion of the subsequent stages. The fuzzy comprehensive evaluation method can quantify the identified risks of engineering projects. By constructing a judgment matrix through the fuzzy comprehensive evaluation method, the maximum eigenvalue and eigenvector were calculated as the weights of each risk factor. The risk danger was ranked according to the size of the weights, and the evaluation factors are determined for the selection of risk control plans. Therefore, this paper has proposed the research on the assessment of project risk control schemes based on the fuzzy comprehensive evaluation method in an uncertain environment, further provided enterprises with a risk control scheme centered on project quality and offering a new idea for each enterprise to select the optimal risk control scheme.

Risk management was referred to the need to formulate corresponding contingency plans for the constantly changing risks in the risk prevention process during the management process, ensuring timely response. In the face of new risk issues, timely assessment and evaluation should be conducted, so as to make appropriate adjustments to the risk management emergency plan and ensure that the new plan can be effectively implemented during the construction process. Ensure that there is a complete risk monitoring plan for each stage of the entire project construction to maintain the dynamic and continuous nature of risk prevention throughout the project construction period, thereby achieving the predetermined prevention effect. Risk identification for large-scale projects and classified the risks were conducted, dividing them into technical and non-technical risks, which is of positive significance for the implementation of risk identification [1]. The content of engineering risk quantification and quantified the relevant risks were proposed, which is helpful for identifying the related risks [2]. The inquiry method was adopted to make the risk list by consulting relevant experts [3]. The checklist method was used to confirm the risk factors of actual cases, that is, risk identification [4]. The Analytic Hierarchy Process (AHP) and fuzzy analysis method was employed to assess and analyze project risks [5]. Its advantage lies in the fact that when evaluating project risks, it can meticulously analyze the impact degree of each risk factor on the entire project, enabling targeted measures to be taken.

The main research content of this article is as follows: Firstly, it has analyzed the positive significance of the selection of risk control schemes in enterprise construction projects. Secondly, from the perspective of risk identification, combined with the common risk contents of enterprise construction projects, the common risks in enterprise construction projects were summarized and sorted out by using methods such as brainstorming, Delphi method and checklist method. Furthermore, based on the identified risks, various risks were evaluated and analyzed from different perspectives using the fuzzy Analytic Hierarchy Process, and specific evaluation results were provided. Finally, for the identified risks, as the evaluation factors of the risk control plan, the weighted scoring method was adopted in combination with the actual case A enterprise construction project risk management research. Through the application of the above risk identification, evaluation and analysis as well as the selection of risk control plans, the above research was improved.

2. Selection methods for risk control plans in engineering projects

The main focus in this article was on the assessment of risk control plans during the construction process of ongoing engineering projects. The objective was to adopt scientific and reasonable methods to identify the main risk factors of construction projects, assess and analyze them, and take appropriate control decisions to reduce risks. The existed risks were unable to be completely avoided. Hence, new strategies were required to control them within an acceptable range through scientific management methods [6]. Based on this, a method for selecting risk control schemes for engineering projects was proposed (refer **Table 1**).

(1) In the process of risk identification for construction projects, the brainstorming method was first adopted to have relevant experts and practitioners identify related risks based on the current situation, and then the identified risks were made into a table, which is the risk checklist. Through this checklist, relevant risks were relatively well identified.

(2) Five managers, five technical engineers and five supervision experts with over 10 years of experience in the industry were selected. The Delphi method was used to have the relevant experts evaluate the identified risks. The opinions of the experts were summarized and the risk factors that the experts all

considered to constitute risks were recorded. After the opinions of the experts tend to be consistent, the relevant factors that the experts consider to have a relatively high risk were scored. The scoring was mainly focused on the occurrence probability of the relevant risk factors. Let the above-mentioned experts score the relevant indicators and take the average value to represent it using the 9-level scaling method. After scoring, a first-level comparison matrix was obtained. Through calculation, the first-level comparison matrix yields the scores of relevant risk factors. After meeting the consistency test, the relative importance levels of each risk factor were obtained.

Table 1. Comprehensive evaluation matrix $\boldsymbol{R} = \left(r_{ij}\right)_{N\times M}$ of alternatives

Plan	G_1	G_2	…	G_M
S_1	r_{11}	r_{12}	…	r_{1M}
S_2	r_{21}	r_{22}	…	r_{2M}
…	…	…	…	…
S_N	r_{N1}	r_{N2}	…	r_{NM}

$$b_{ij} = ln\left(1/a_{ij}\right) \; (i = 1,2,\ldots,N, \quad j = 1,2,\ldots,M) \tag{1}$$

$$Z_i = \sum_{j=1}^{M} \rho_{\text{nom}j} b_{ij} \; (i = 1,2,\ldots,N, \quad j = 1,2,\ldots,M) \tag{2}$$

(3) The standard scale scoring method was used to determine S. This method has usually provided different standard scoring values, such as 1–5 or 1–10 points, and used the size of the score to determine the degree to which the scheme meets the evaluation objective. Based on the weights obtained from the expert evaluation team information, the comprehensive information volume of the alternative plans was calculated, and its calculation formula was shown below.

$$R_i = \sum_{j=1}^{M} Z_i s_{ij} \; (i = 1,2,\ldots,N, \quad j = 1,2,\ldots,M) \tag{3}$$

Risk identification was conducted for engineering projects by adopting the brainstorming method. After risk identification, the Delphi method was used to reanalyze the previously determined risks, that is, to quantify the risks. Then, the fuzzy analytic Hierarchy process was used to create a judgment matrix. Finally, the weights were processed to determine the risk level. The optimal risk control plan was selected through the weighted scoring method.

3. Examples and analysis of results

Although the construction project of Company A has involved in the expansion of the company's factory buildings and dormitories, the main project was still a building project. It has similar characteristics to general construction projects and thus has a certain degree of universality. Then, during the risk analysis of the construction project of Company A, general construction project cases was referred to. Meanwhile, the analysis and evaluation research of the risk control plan of the construction project of Company A have provided a reference for the relevant analysis of other construction projects to a certain extent. In accordance with the content of the risk control plan selection method, starting from risk identification, evaluation and analysis. A further analysis of this project was conducted. Based on the relevant contents of risk identification and evaluation analysis, the risk control plan for the construction project of Enterprise A was selected.

(1) From the risk checklist of the engineering project design stage, it was known that during the design stage of the construction project of Company A, this study has focused on identifying the risks of process and flow, technical and usage risks, the rationality of design, the accuracy of background information, and risks related to the working environment. On the basis of these identified risk factors, this study has further refined the analysis.

(2) Due to the excessive number of risk factors proposed by the project team of Company A during the brainstorming session, this study has identified and analyzed these risk factors. By re-analyze the contents of the risk checklist mentioned above through the Delphi method, and select managers, technicians, and supervisors with over 10 years of experience in this industry, risks have been identified. The risk factors that all experts consider to constitute risks have been identified, as shown in **Table 2**.

Table 2. The main risks of engineering projects and the weights

The main risks	Contents of risks	The weights
Materials of equipment	The quality, progress and personnel safety of construction projects are affected due to the substandard construction machinery and building materials	C1 (0.147)
Safety risk	The prevention measures are inadequate and the risk control plan is incomplete	C2 (0.196)
Personnel risk	Insufficient safety awareness among on-site construction workers	C3 (0.657)
Policy risk	Refers to changes in relevant government policies	C4 (0.122)
Financial risk	The risk caused by excessively high procurement costs of materials	C5 (0.558)
Quality management	Materials and equipment were substandard	C6 (0.320)
Contract risk	Risks arise due to loopholes in the contract	C7 (0.494)
Supplier management	Risks arising from suppliers' non-compliance with contracts	C8 (0.266)
Design plan	Implemented in accordance with laws and regulations	C9 (0.240)
Technology	Technologies cannot be utilized	C10 (0.230)
Economic risks	The overall situation of the financial market	C11 (0.648)
The working environment	The climate, water quality and other conditions at the construction site	C12 (0.122)

Based on the relevant analysis of the weight ranking of risk factors, it was concluded in the first-level risk factor indicators that management risk was higher than technical risk, technical risk was higher than construction risk, and construction risk was higher than environmental risk. According to Equation (1) and (2), the most significant risk factors for Company A's construction projects were: technical and operational risks, political risks, contract management, equipment and materials, supplier management, and safety risks.

(3) Considering the actual situation of the engineering project, the expert team has determined three alternative risk control plans for the construction project of Company A and has selected five employee representatives (D1 to D5) from among the numerous employees of Company A to evaluate the three alternative plans. Based on the risk factor analysis and evaluation of the construction project of Enterprise A, it was concluded that the risk factors affecting the project was divided into two layers. The first layer was the project layer, and the second layer was the criterion layer, mainly the specific factors that have an impact on the project. The weight ranking was obtained by the fuzzy comprehensive evaluation method. Select the top five as the key evaluation index factors for the weighted scoring method. Factor set F = {F1: Technology and Application, F2: Policy Risk, F3: Contract Management, F4: Equipment and Materials,

F5: Supplier Management}. The normalized index weight vector was obtained by using the improved weighted average method as $\tilde{\boldsymbol{n}}_{\text{norm}} = (0.20, \quad 0.14, \quad 0.22, \quad 0.31, \quad 0.13)$.

(4) The expert team thoroughly analyzed the existing scheme information. Five experts have reviewed the initial design values of the scheme to obtain the evaluation values. The experts have obtained the relative weights of each expert through voting. Based on the expert weights, the comprehensive evaluation values were obtained to construct the evaluation matrix (**Table 3**).

Table 3. The evaluation information of five alternatives

	R_1	R_2	R_3
D_1	0.46	1.00	0.76
D_2	1.00	1.00	0.77
D_3	0.38	1.00	0.73
D_4	0.63	1.00	0.83
D_5	0.00	0.00	1.00

Based on Equation (11), the comprehensive assessment values of the alternative risk control plan for this project were obtained as: $R_1 = 2.57$, $R_2 = 3.54$, $R_3 = 3.53$. Therefore, R_2 was the optimal risk control scheme.

To further verify the effectiveness of the method, after the enterprise applied the results and analyzed the feedback information from the project implementation department, the results were recognized. The application of this method also indirectly brought the following benefits to the enterprise: It has reduced problems such as project delays, cost overruns, and substandard quality, lowered economic losses and resource waste, safeguarded the rights and interests of all parties involved in construction, operation, and supervision, and avoided disputes. At the same time, by optimizing processes and standardizing operations, the project management level was enhanced to accumulate reusable experience for subsequent projects and ensure the smooth fulfillment and delivery of the projects.

4. Conclusions

Based on domestic and international research and in accordance with the actual situation of engineering enterprises in China, this paper has analyzed the main influencing factors of digital transformation of engineering enterprises, and has constructed an evaluation index system for the maturity of digital transformation of engineering enterprises from four aspects, by using the G_1 method to obtain the index weights, and finally applied the cloud model to evaluate the maturity of digital transformation of engineering enterprises.

(1) Based on current standards and norms, this paper has analyzed the influencing factors of digital transformation in engineering enterprises by establishing index principles and bases, and uses principal component analysis to screen the influencing factors of digital transformation in engineering enterprises, eliminating secondary indicators An evaluation index system for the maturity of digital transformation of engineering enterprises has been established, which includes four first-level indicators: digital operation technology, digital system guarantee and digital foundation, and digital performance, nine second-level indicators, and 24 third-level indicators.

(2) By using G_1 to calculate the weights of the evaluation indicators for the digital transformation maturity of engineering enterprises, it can be understood that the degree of influence of intelligence level, total factor productivity, digital strategy formulation, digital strategy matching, and management decision-

making efficiency on the digital transformation maturity of engineering enterprises is relatively large. Corresponding measures can be taken during the digital transformation process. Accelerate the digital transformation of engineering enterprises.

(3) This paper has employed a cloud model to evaluate the maturity level of digital transformation in engineering enterprises, which can effectively address the ambiguity and randomness of the evaluation, complete the conversion between qualitative expression and quantitative values of maturity evaluation, and make the evaluation more objective and reasonable.

Disclosure statement

The author declares no conflict of interest

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Study on Asymmetric Deformation Patterns in Layered Soft Rock Tunnels

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Abstract: Layered rock mass is a typical complex rock mass. Owing to its layered structure, its deformation and strength properties exhibit distinct anisotropic characteristics. Taking a deep-excavated railway tunnel as the engineering context, this study investigates the asymmetric deformation laws of layered soft rock tunnels from two perspectives: laboratory tests and numerical simulations. Uniaxial saturated compression tests were conducted to analyze the anisotropic mechanical characteristics of rock bedding planes. This study established a model of layered rock mass tunnel excavation and support. From the perspectives of tunnel peripheral displacement, plastic zone, and maximum principal stress, it reveals the asymmetric deformation characteristics of the surrounding rock under different dip angles of bedding planes. These findings provide valuable insights for the construction of high-stress layered soft rock tunnels.

Keywords: Layered soft rock tunnels; Carboniferous slate; Asymmetric deformation; Anisotropy

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1. Introduction

1.1. Background

Railway tunnel construction often faces the impact of high in-situ stress, high seismic intensity, and complex tectonic stress fields. Beyond these challenges, a common characteristic is traversing stratigraphic formations composed of carbonaceous shale, phyllite, and other layered, weak strata. These formations exhibit poor mechanical properties and low self-stabilizing capacity, leading to issues such as spalling and failure of initial support, as well as distortion and deformation of rigid arches. These issues pose significant challenges to both the construction and operation stages of the tunnel. Existing research has established a fundamental theoretical framework for the deformation mechanisms of layered soft rock, with existing research primarily focusing on lateral pressure issues caused by topography and weak interlayers [1–12]. However, the constitutive behavior of the surrounding rock remains the dominant factor governing the evolution of large deformations. Based on a deep-excavated railway tunnel, this paper studies and analyzes the influence of bedding plane occurrence on the asymmetric deformation laws of layered soft rock tunnels by means of laboratory tests and numerical simulations.

1.2. Project overview

The tunnel is a high-altitude double-track, twin-bore railway tunnel. The portal elevation is approximately 2,735 meters, while the exit elevation is approximately 3,260 meters, presenting an elevation difference of 525 meters. The track spacing is 45 meters, with a maximum burial depth of approximately 670 meters. The surrounding rock is complex and variable in lithology, predominantly consisting of slate with local intercalations of sandstone. The schist exhibits a predominantly microcrystalline mudstone texture with localized sandy structures, exhibiting extremely thin-bedded formations typically less than 1 cm thick. Inter-bedding cohesion is poor, classifying it as weak rock mass. This poses a significant risk of large deformation due to compression during excavation. The tunnel zone traverses strata within joint zones and densely jointed areas, predominantly oriented NE with predominant dip directions of 100° to 150°, generally exhibiting steep dip angles. Joint spacing generally ranges from 0.5 to 2.0 meters, with extensions exceeding 1.0 meter. Most joints are either closed or slightly open, lacking infill and exhibiting relatively straight orientations. Statistical analysis of joint dip directions and dip angles for the Triassic Longwu River Formation is presented in **Figure 1**. In-situ stress testing was conducted across 29 measurement sections within six deep boreholes in the tunnel zone. As shown in **Figure 2**, the maximum horizontal principal stress reached 22.88 MPa, classifying this as a high-to-extremely high in-situ stress zone.

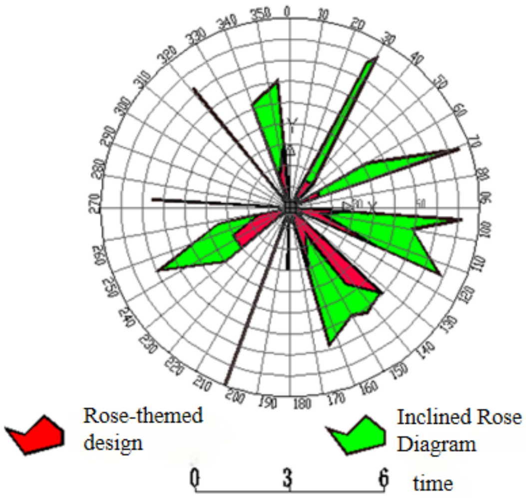


Figure 1. Rose-shaped joint pattern.

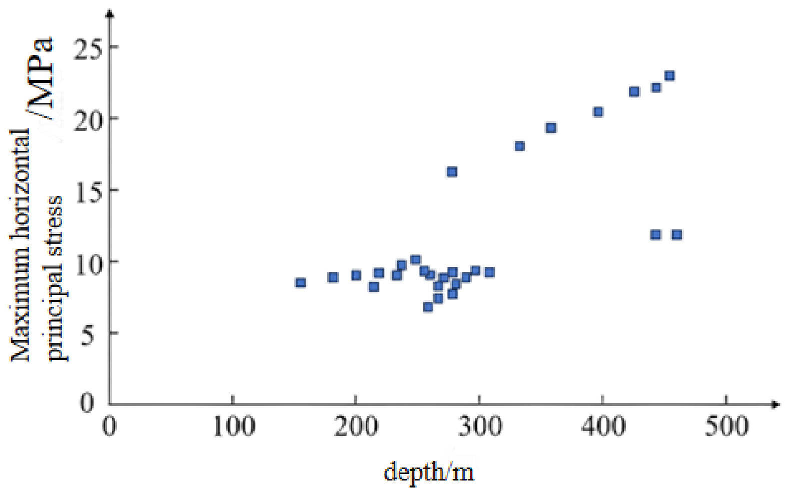


Figure 2. Relationship between maximum horizontal principal stress and tunnel depth.

2. Rock mass mechanical properties

To investigate the mechanical properties of rock blocks with varying bedding plane angles, thin-bedded jointed rock blocks predominantly composed of carbonaceous shale were selected. All specimens were extracted from the same excavation cross-section within the tunnel. Owing to the distinctive thin-bedded sedimentary structure of carbonaceous slate, the sampling success rate was low, and the specimens were not derived from a single block. Carbonaceous slate specimens were drilled at five angles: 0°, 30°, 45°, 60°, and 90°. The specimens were cylindrical in shape, with a diameter of 50 mm and a length of 10 mm, tolerances of ± 0.5 mm, and end-face parallelism of ± 0.02 mm. Uniaxial saturated compressive strength tests were conducted on carbonaceous slate specimens with different bedding plane orientations. The results obtained from these tests are presented in **Figure 3**.

dip	dip-0°	dip-30°	dip-45°	dip-60°	dip-90°
Ultimate compressive strength/MPa	23.12	16.67	9.44	18.87	37.35
Secant Elastic ModulusE50/GPa	23.07	4.98	4.20	4.58	34.52

Figure 3. Mechanical properties of specimens at different inclination angles.

The test results indicate

(1) The ultimate compressive strength and secant modulus of rock specimens obtained from uniaxial compression tests reveal pronounced anisotropic mechanical properties in layered carbonaceous shale. Analysis of failure characteristics across different bedding plane orientations indicates that the weak bedding planes constitute the primary factor influencing the rock mass’s anisotropic mechanical behavior. The uniaxial saturated compressive strength and secant modulus of the rock blocks exhibit a U-shaped variation with respect to the bedding plane angle.

(2) When the loading direction is parallel to the bedding plane (bedding plane angle 90°), both the ultimate compressive strength and secant modulus are greater than when the loading direction is perpendicular to the bedding plane (bedding plane angle 0°). At a bedding plane angle of 45°, both ultimate compressive strength and tangent modulus of elasticity attain their minimum values. The uniaxial saturated compressive strength of rock blocks at different angles provides a partial explanation for the occurrence of buckling failure in tunnels through layered soft rock.

3. Study on the physical field characteristics of three-layered soft rock tunnels

3.1. Stratigraphic-structural model and selection of constitutive parameters

The Ubiquitous-Anisotropic model is based on the Mohr-Coulomb constitutive relationship, adhering to the Mohr-Coulomb yield criterion. It incorporates anisotropic constitutive behavior by embedding weak planes oriented in specific directions. The geological formation traversed by the tunnel consists of carbonaceous laminated schist, exhibiting pronounced anisotropic mechanical characteristics. Physical and mechanical parameters of the rock mass were determined in accordance with the Technical Specification for Railway Tunnels in Compressible Surrounding Rock. A ubiquitous jointed constitutive model was employed to simulate the excavation of a layered soft rock tunnel, with the parameters used for simulation shown in **Table 1**.

Table 1. Constitutive parameters

Constitutive parameters	Unit	Parameter range
dip	°	0–90
dip-direction	°	90
joint-cohesion	MPa	0.6
joint-friction	°	25
joint-tension	GPa	0.18
young-plane	GPa	1.2
young-normal	GPa	0.5
poisson-plane	/	0.4
poisson-normal	/	0.2
density	kg/m^3	2000

The computational model employs the actual cross-sectional dimensions of the tunnel, as illustrated in **Figure 4**. Support parameters are classified as Grade V, with the tunnel buried at a depth of 600 meters. The fundamental assumptions for the geological-structural model are as follows:

(1) Both stress and strain in the strata and support parameters remain within the elastic-plastic range

(2) The influence of tunnel excavation on rock mechanical parameters is disregarded

(3) The effects of groundwater seepage are not considered

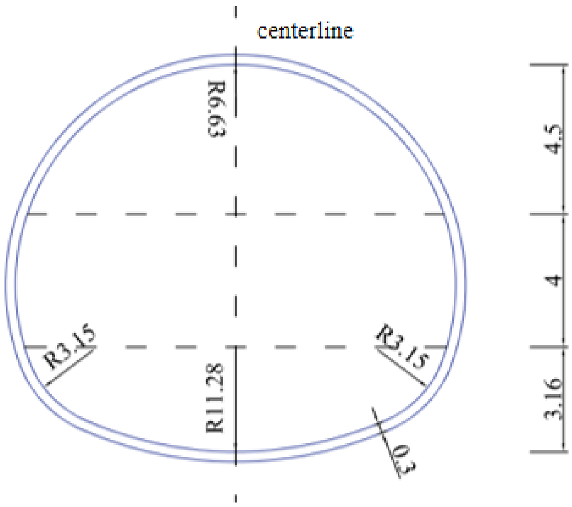
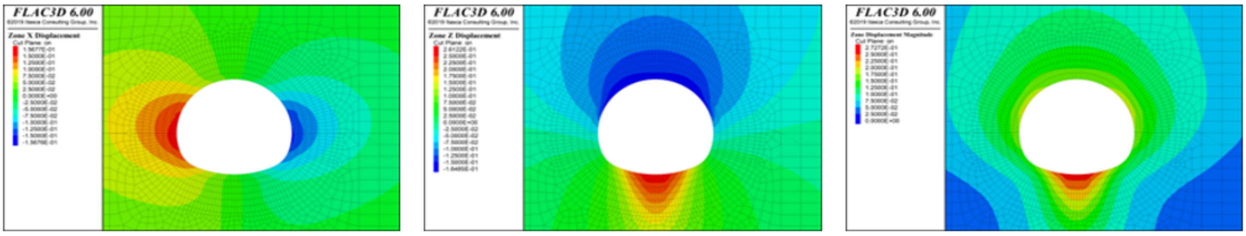


Figure 4. Tunnel cross-section diagram.

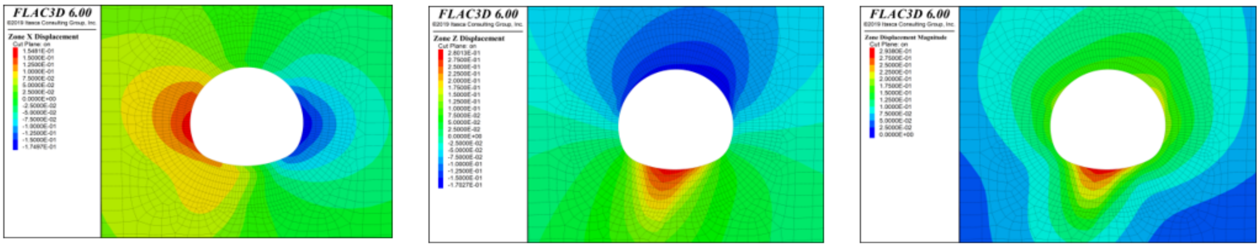
3.2. Perforation displacement

Following completion of the tunnel excavation, horizontal displacement, vertical displacement, and combined displacement contour plots under different inclination conditions for the same stratigraphic plane inclination were selected at the mid-section (Y = 60 m), as shown in **Figures 5** to **11**.



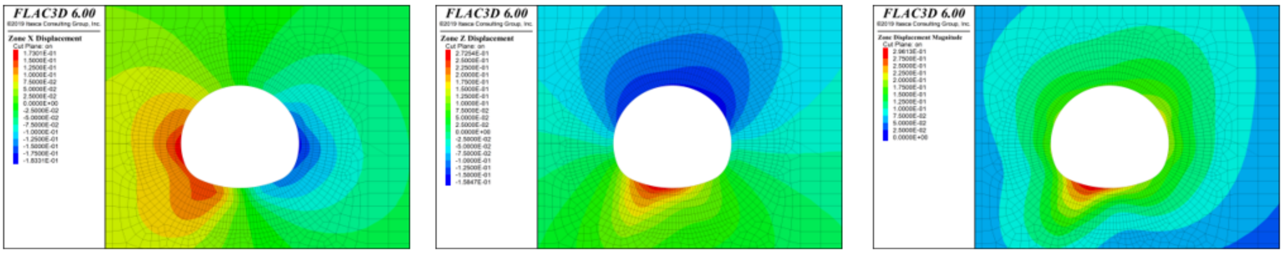
(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 5. dip-0°.



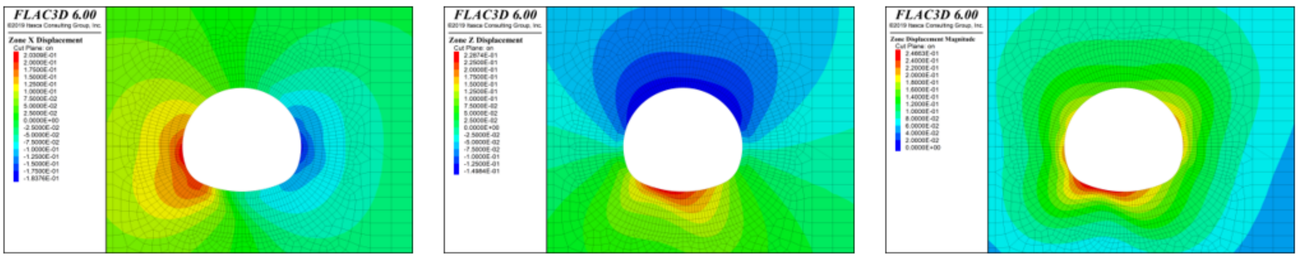
(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 6. dip-15°.



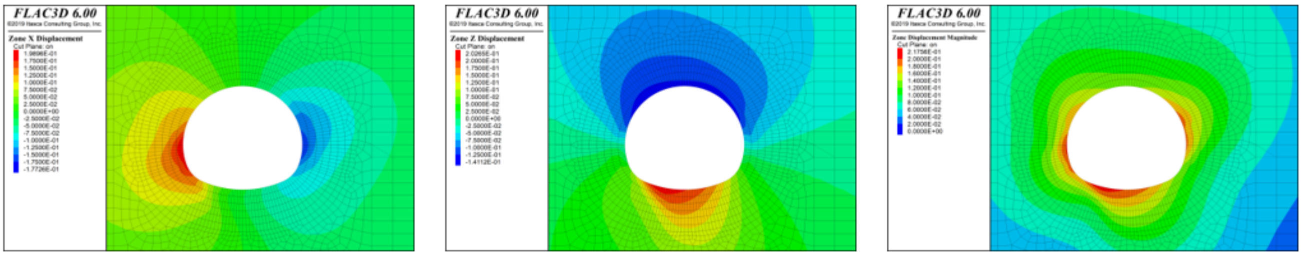
(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 7. dip-30°.



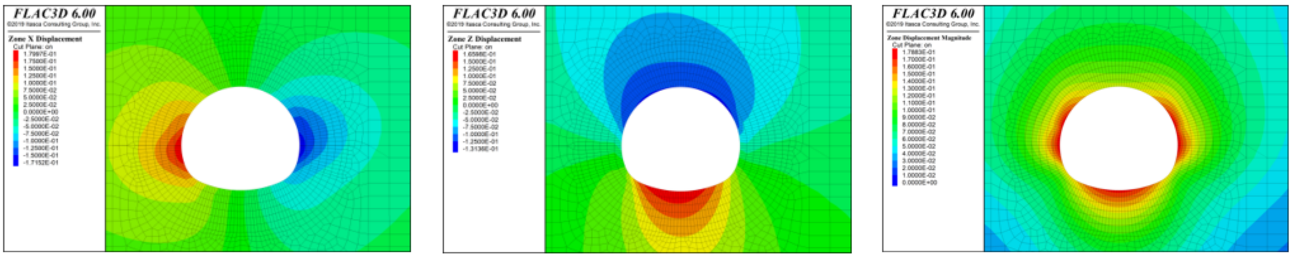
(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 8. dip-45°.



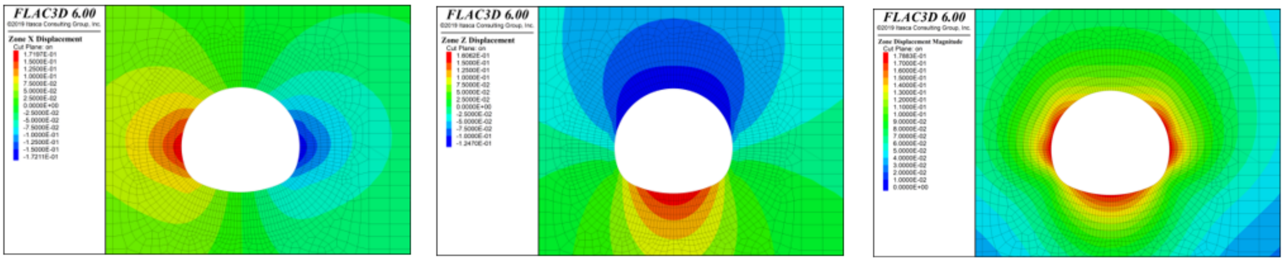
(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 9. dip-60°.



(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 10. dip-75°.



(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 11. dip-90°.

From the deformation characteristics observed around the rock cavities at different stratigraphic dip angles (see **Table 2**), it can be seen that:

(1) The deformation characteristics of the tunnel perimeter in layered soft rock tunnels vary with the dip angle of the bedding plane. Except for dip angles of 0° and 90°, both the horizontal and vertical displacements of the tunnel perimeter differ from those in homogeneous rock masses, exhibiting distinct asymmetric features. The location of maximum deformation in the surrounding rock gradually shifts from the invert and crown towards the left and right sidewalls, with the primary deformation zone changing as the position deviates from the normal to the bedding plane.

(2) In layered soft rock tunnels, the vertical relative convergence value decreases with increasing dip angle, while the horizontal relative convergence value first increases then decreases. When the dip angle exceeds 45°, the horizontal relative convergence value around the tunnel exceeds the vertical relative convergence value, and the dominant displacement direction shifts from vertical to horizontal deformation.

It is evident that the weak-zone effect within layered rock formations exerts a significant influence on the deformation characteristics of tunnel surrounding rock, constituting the primary cause of asymmetric displacement patterns around the tunnel borehole. Consequently, during the construction of tunnels through layered soft rock, support measures must be specifically designed to address the distinct orientations of different bedding planes.

Table 2. Deformation displacement values around the tunnel

Dip	Vaulted ceiling sagging /mm	Cambered arch /mm	Maximum horizontal displacement on the left side /mm	Maximum horizontal displacement on the right /mm	Maximum deformation /mm
0°	-164.8	261.2	156.7	-156.7	272.7
15°	-170.2	280.2	154.8	-174.9	293.8
30°	-158.4	272.5	173.0	-183.3	296.1
45°	-149.8	228.7	203.0	-183.7	246.6
60°	-141.1	202.6	198.9	-177.2	217.5
75°	-131.3	165.9	179.9	-171.1	185.9
90°	-124.7	160.6	171.9	-172.1	178.8

3.3. Distribution of plastic zones

The stability of the rock mass-support system is governed by the shallow rock mass (loose zone, plastic zone). The presence and distribution characteristics of the plastic zone exert a significant influence on the load-bearing properties of the support structure. With a lateral pressure coefficient of 1.2 and a dip of 90°, the distribution of the plastic zone under different bedding plane inclinations is illustrated in **Figure 12**.

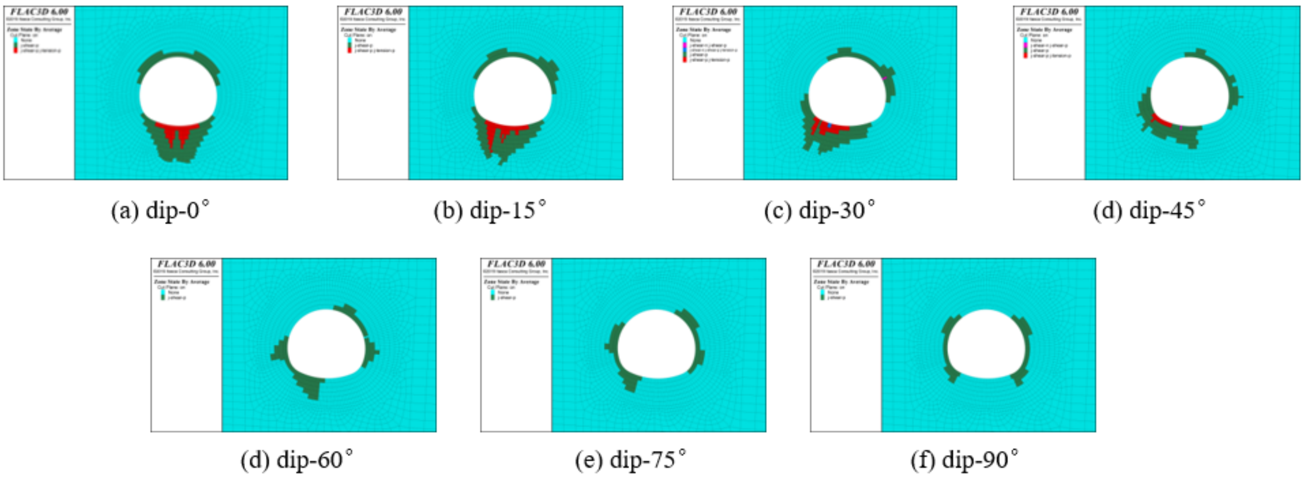


Figure 12. Plastic zone distribution.

From the distribution of the plastic zone at different inclination angles (see **Table 3**), it can be seen that:

(1) The maximum depth of plastic zones at the crown and base of the arch diminishes as the dip angle of bedding planes increases. Within the 0° to 30° dip range, plastic zones exhibit greater depth at the crown and invert positions, with the invert region displaying deeper plastic zones than the crown area. Overall distribution indicates plastic zones predominantly occur along the normal direction of bedding planes.

(2) The primary distribution of the plastic zone within the surrounding rock is significantly influenced by the dip angle of the strata. As the dip angle of the bedding plane varies from 0° to 90°, the main distribution area of the plastic zone shifts from the crown and invert towards the abutments and side

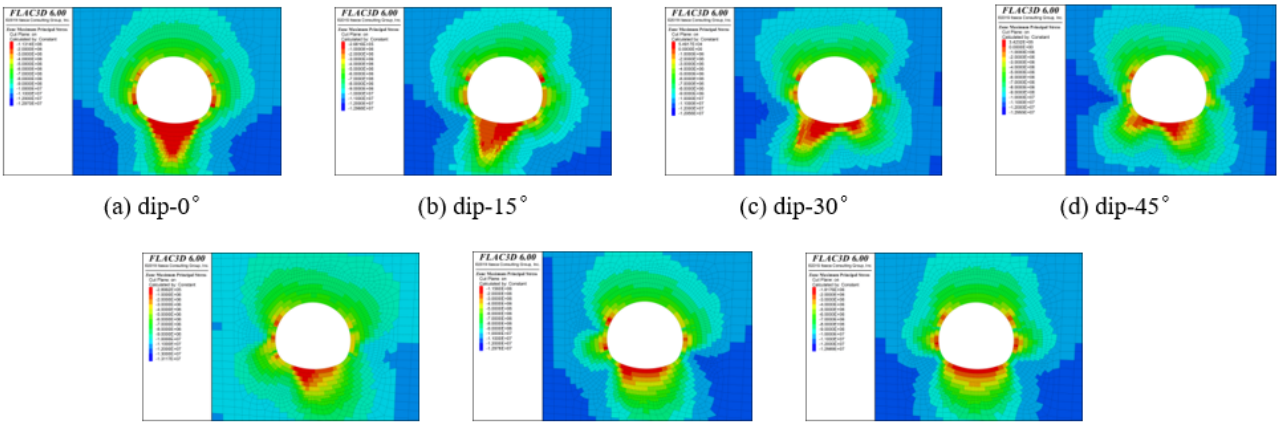
walls. This pattern parallels the evolution of the displacement field around the tunnel, transitioning from predominantly vertical deformation to predominantly horizontal deformation.

Table 3. Maximum depth of plastic zone at different inclination angles and positions

Dip	Location of the plastic zone			
	Tunnel crown /m	Tunnel invert /m	Tunnel abutment /m	Tunnel sidewall /m
0°	1.6	5.6	1.6	0.8
15°	1.6	5.6	2.4	0.8
30°	1.6	4.8	0.8	1.6
45°	1.6	4	0.8	2.4
60°	0.8	4	1.6	3.2
75°	0.8	3.2	1.6	1.6
90°	0	0	1.6	0.8

3.4. Analysis of maximum principal stress

Following tunnel excavation, the original stress equilibrium state of the surrounding rock is disrupted, leading to stress redistribution within the adjacent rock mass. Consequently, both the magnitude and direction of the maximum principal stress undergo alteration. Analyzing the influence of bedding plane weakness from the perspective of maximum principal stress, the stress distribution map for a bedding plane inclination with a lateral pressure coefficient of 1.2 and varying bedding plane dips is illustrated in **Figure 13**.



(a) dip-0° (b) dip-15° (c) dip-30° (d) dip-45°

(d) dip-60° (e) dip-75° (f) dip-90°

Figure 13. Contour map of maximum principal stress.

The calculation results (see **Table 4**) indicate that:

(1) The distribution characteristics of the maximum principal stress in the surrounding rock exhibit deflection with changes in the dip angle of the bedding plane, displaying an asymmetric pattern similar to the distribution patterns of tunnel perimeter displacement and plastic zones. The maximum principal stress in the surrounding rock around the tunnel is predominantly compressive. Within the zones of low absolute values for maximum principal stress, deformation in the surrounding rock is significant, and the direction of deflection of the maximum principal stress aligns with the normal direction of the bedding plane.

(2) As the dip angle of the bedding plane increases, the minimum absolute value of the maximum principal

stress exhibits a U-shaped variation pattern. Within zones of low maximum principal stress, significant deformation occurs in the surrounding rock. The maximum displacement around the tunnel first increases and then decreases, displaying identical deformation characteristics. This indicates a close correlation between rock mass deformation and the maximum principal stress.

Table 4. Maximum principal stress at different stratification surface inclinations

Dip	0°	15°	30°	45°	60°	75°	90°
Minimum absolute value of the maximum principal stress/MPa	-1.13	-0.268	0.054	0.342	-0.289	-1.15	-1.81

4. Conclusion

This study is based on laboratory uniaxial saturated compression tests on carbonaceous slate with different dip angles. By comprehensively considering rock mechanical properties and numerical simulation analysis, it investigates the influence of bedding plane occurrence on the laws of large deformation in layered soft rock tunnels from three dimensions: tunnel peripheral displacement, plastic zone distribution, and maximum principal stress. Conclusions are as follows.

(1) The distribution laws of tunnel peripheral displacement and plastic zones in layered soft rock tunnels are significantly affected by bedding plane occurrence. Compared with homogeneous rock masses, they exhibit asymmetric and non-uniform deformation characteristics. Specifically, during the transition from horizontal layered rock strata to steeply dipping layered rock strata, the deformation mode changes from vertical deformation to horizontal deformation.

(2) With the increase of bedding plane dip angle, the minimum value of the absolute value of the maximum principal stress shows a "U"-shaped variation trend. The maximum peripheral displacement of the tunnel first increases and then decreases. The low-value areas of the maximum principal stress and the locations of maximum deformation in the surrounding rock around the tunnel exhibit the same deformation characteristics, indicating a close relationship between the deformation of the surrounding rock and the maximum principal stress.

(3) Given that the deformation characteristics of layered soft rock tunnels are significantly affected by bedding plane occurrence and exhibit obvious asymmetric features, specific designed support measures should be adopted for different bedding plane occurrences in actual tunnel engineering construction. For areas with large deformation (in the normal direction of bedding planes), measures such as increasing the number of bolts and applying anchor cables can be used to reinforce the surrounding rock to restrict its deformation.

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Disclosure statement

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Construction Management of HVAC Engineering in Real Estate: Key Strategies for Quality Control

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Abstract: This research focuses on quality control strategies in real estate HVAC engineering construction management. It first elaborates on the role of HVAC systems and challenges like material compliance risks and installation deficiencies. Then it details design validation, vendor qualification, and construction–phase monitoring methods. Case studies in various real estate projects illustrate these strategies, and a 5-phase quality maturity model was proposed for quality improvement.

Keywords: HVAC engineering; Quality control; Real estate construction

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1. Introduction

In the real estate development landscape, HVAC engineering is fundamental, influencing comfort, functionality, and energy efficiency. However, its construction management faces quality challenges like system design issues, installation problems, and interdisciplinary coordination difficulties [1]. In response to such concerns, the US Department of Energy's "Better Buildings Initiative" launched in 2011 aims to improve the energy efficiency of commercial and residential buildings, which is closely related to HVAC system performance. This research focuses on identifying key quality–control strategies for HVAC construction management in real estate. It analyzes existing problems to offer practical solutions, contributing to enhanced HVAC installation quality, overall real estate value, and the sustainability of the built environment.

2. HVAC system fundamentals in real estate

2.1. Core components of HVAC systems

HVAC systems in real estate consist of several core components that work in harmony to provide comfortable indoor environments. Ductwork design is a crucial part, especially in high rise residential and commercial buildings. The ducts are responsible for transporting conditioned air throughout the building. Their design must account for factors like air pressure, air velocity, and proper sizing to ensure efficient air distribution. Incorrect ductwork design can lead to uneven temperatures, poor air quality, and increased energy consumption [2].

The refrigeration cycle is another essential core component. It is the mechanism by which heat is removed from indoor spaces. In HVAC systems, refrigerants play a vital role in this cycle. They absorb heat from the indoor air, get compressed, release the heat outside, and then expand to repeat the cycle. This process enables the cooling of the air that is then distributed to the building's interior.

Air distribution networks are also key. These networks include diffusers, grilles, and registers. They are responsible for releasing the conditioned air into the occupied spaces in a way that creates a comfortable environment. The location, size, and type of these components impact how well the air is distributed. For example, in a large commercial space, the right choice of diffusers can ensure uniform temperature distribution across the area, while in a high rise residential building, proper grille placement can enhance the comfort of individual apartments. All these core components, when properly designed and integrated, are essential for the effective operation of HVAC systems in real estate projects.

2.2. Interdisciplinary coordination requirements

The interface management between HVAC systems, structural engineering, and architectural elements is of utmost importance in preventing spatial conflicts during installation in real estate projects. For instance, HVAC ducts need to be carefully planned to ensure they do not encroach upon the space allocated for structural components like beams and columns. If not coordinated properly, the installation of large scale HVAC equipment might require modifications to the structural design, which can be time consuming and costly [3].

Architectural elements also play a crucial role. The layout of rooms, ceilings, and walls can significantly impact the installation and functionality of HVAC systems. HVAC designers must collaborate closely with architects to ensure that air vents, diffusers, and other components are integrated seamlessly into the building's aesthetic design. This includes considerations such as the location of air handling units to avoid visual disruptions in the interior space.

Moreover, electrical and plumbing systems are also part of this interdisciplinary equation. HVAC systems rely on electrical power, and proper coordination is needed to ensure that electrical conduits do not interfere with the routing of HVAC ducts. Similarly, plumbing lines should be planned in a way that they do not conflict with the installation and maintenance requirements of HVAC systems. In essence, effective interdisciplinary coordination is the linchpin for successful HVAC system installation in real estate, ensuring that all aspects of the building's design and construction work in harmony to achieve optimal functionality and quality.

3. Quality challenges in HVAC construction

3.1. Material compliance risks

Supply chain vulnerabilities can significantly contribute to material compliance risks in HVAC construction within real estate projects. These vulnerabilities often lead to the procurement of substandard equipment, which is a major concern. For instance, suppliers facing financial difficulties may cut corners in production to reduce costs, resulting in HVAC materials that do not meet the required quality and performance standards. This can include components with inferior durability, lower energy efficiency, or improper sizing.

Non-compliance with standards such as those set by ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) is another significant issue. ASHRAE standards are widely recognized as benchmarks for HVAC systems, covering aspects like energy efficiency, indoor air quality, and system design. Failure to adhere to these standards can lead to a range of problems. For example, an HVAC system that does not meet ASHRAE's energy efficiency requirements may consume excessive energy, increasing operational costs for the building owner. Moreover, non-compliance in terms of indoor air quality standards can have adverse impacts on the health and comfort of the building occupants. Inadequate filtration or ventilation due to non-compliant materials can lead to the spread of pollutants, allergens, and pathogens within the building. Overall, addressing material compliance risks is crucial for ensuring the quality and proper functioning of HVAC systems in real estate construction [4].

3.2. Installation precision deficiencies

During the on-site implementation phases of HVAC construction in real estate projects, there are several recurring installation precision deficiencies that pose significant quality challenges.

Equipment calibration is a prime area of concern. Incorrect calibration of HVAC equipment can lead to suboptimal performance. For example, if the thermostat is miscalibrated, it may not accurately sense the indoor temperature, resulting in either overcooling or overheating. This not only affects the comfort of the building occupants but also increases energy consumption. In some cases, the refrigerant charge in air conditioning units may be set incorrectly during installation, which can reduce the system's cooling capacity and efficiency [5].

Duct sealing is another aspect where precision is crucial. Leaky ducts can cause significant energy losses. During installation, if the joints between duct sections are not properly sealed, conditioned air can escape into unconditioned spaces. This not only wastes energy but also disrupts the air distribution within the building. For instance, in large commercial buildings, unsealed ducts can lead to temperature variations between different zones, making it difficult to maintain a consistent indoor environment.

Piping insulation installation also demands high precision. Poorly installed piping insulation can result in heat transfer between the pipes and the surrounding environment. In chilled water piping systems, inadequate insulation can cause condensation on the outer surface of the pipes, which may lead to water damage to the building structure over time. Additionally, if the insulation is not properly sized or installed around hot water pipes, heat loss occurs, reducing the efficiency of the heating system. These installation precision deficiencies in equipment calibration, duct sealing, and piping insulation must be addressed to ensure the overall quality of HVAC construction in real estate projects.

4. Strategic quality control frameworks

4.1. Preconstruction quality assurance

4.1.1. Design validation protocols

Design Validation Protocols play a pivotal role in pre-construction quality assurance for HVAC engineering in real estate. These protocols ensure that the HVAC design aligns with the project's requirements, performance expectations, and industry standards.

One key aspect is the use of BIM based clash detection methodologies [6]. BIM (Building Information Modeling) provides a 3D digital representation of the building and its systems. By integrating the HVAC design into the BIM model, engineers can identify potential clashes between the HVAC components and other building elements, such as structural members, plumbing pipes, or electrical conduits. This early detection allows for timely design adjustments, reducing the risk of costly rework during construction.

Energy modeling techniques are also integral to design validation. Energy models simulate the performance of the HVAC system under different conditions, including varying weather patterns and occupancy loads. This helps in evaluating the energy efficiency of the design, ensuring that it meets the energy saving goals of the real estate project. For instance, by analyzing the model results, engineers can optimize the size and type of HVAC equipment, adjust the duct layout for better air distribution, or select more energy efficient control strategies.

In addition, design validation protocols should involve a comprehensive review of the design documents. This includes checking the accuracy of specifications, ensuring that all regulatory requirements are met, and verifying that the design can be effectively implemented during construction. Through these design validation protocols, the quality of the HVAC design can be significantly enhanced, laying a solid foundation for the successful construction and operation of the HVAC system in real estate projects.

4.1.2. Vendor qualification systems

To ensure the quality of HVAC engineering in real estate construction, a comprehensive vendor qualification system is essential. A weighted evaluation matrix incorporating lifecycle cost analysis can be utilized to assess HVAC equipment suppliers [7]. This matrix assigns different weights to various criteria such as product quality, price, reputation, technical capabilities, and after sales service. Product quality is a fundamental factor, which includes aspects like durability, energy efficiency, and compliance with industry standards. Suppliers with high quality products are more likely to contribute to the long term performance of the HVAC system.

Price, although important, should not be the sole determinant. Considering the lifecycle cost analysis, a seemingly cheaper product may incur higher costs in terms of energy consumption, maintenance, and replacement over its lifespan. Therefore, the weighted evaluation matrix helps balance the initial investment with the long-term expenses. Reputation reflects a supplier's track record in the industry. A vendor with a good reputation is more likely to adhere to ethical business practices and deliver reliable products. Technical capabilities are crucial as well, especially when dealing with complex HVAC systems. Suppliers with advanced technical know-how can offer innovative solutions that optimize system performance. Finally, after sales service ensures that any issues with the HVAC equipment can be promptly addressed, minimizing downtime and maintaining customer satisfaction. By using this weighted evaluation matrix, real estate developers can select the most suitable HVAC equipment suppliers, laying a solid foundation for the quality control of HVAC engineering.

4.2. Construction phase monitoring

4.2.1. Real-time sensor integration

Real-Time Sensor Integration is a crucial aspect of Construction Phase Monitoring in the strategic quality control frameworks for HVAC engineering in real estate. Wireless sensor networks play a pivotal role here, enabling IoT enabled monitoring of refrigerant pressures and airflow rates [8]. By integrating real time sensors, construction managers can gain immediate insights into the system's performance. For refrigerant pressures, sensors can detect any deviations from the optimal range. Abnormal refrigerant pressures can lead to inefficient cooling or heating, increased energy consumption, and potential damage to the HVAC equipment. Timely detection allows for prompt corrective actions, such as adjusting refrigerant levels or checking for leaks. Regarding airflow rates, sensors can ensure that the ventilation in the building is adequate. Insufficient airflow can result in poor indoor air quality, discomfort for occupants, and potential health issues. Real time sensor data not only helps in identifying problems during the construction phase but also provides valuable information for fine tuning the HVAC system. This way, it contributes to the overall quality control of the HVAC engineering, ensuring that the system functions optimally and meets the requirements of the real estate project.

4.2.2. Statistical process control (SPC)

SPC is a crucial aspect in the construction phase monitoring of HVAC engineering in real estate for quality control. SPC involves the use of control charts, which are applied for vibration analysis in mechanical rooms. These control charts help in detecting any abnormal variations in the vibration levels of HVAC equipment. By continuously monitoring the vibration parameters, potential mechanical issues such as misalignment, imbalance, or component wear can be identified at an early stage. This allows for timely corrective actions, preventing major breakdowns and ensuring the smooth operation of the HVAC system in the long run.

In addition, thermal imaging is employed for insulation integrity verification. Thermal imaging cameras can detect temperature differences on the surfaces of insulated components. Any areas with abnormal heat loss or gain indicate potential insulation problems. SPC techniques can be used to analyze the thermal imaging data, setting control limits to distinguish between normal and abnormal temperature patterns. This helps in maintaining the energy efficiency of the HVAC system as proper insulation reduces heat transfer and energy consumption. By using these SPC based methods like control charts for vibration and thermal imaging analysis, construction managers can ensure that the HVAC engineering meets high quality standards and functions optimally [9].

5. Implementation case studies

5.1. High-density residential project

5.1.1. Vertical stack optimization

In the high-density residential project of a 50-story tower with a variable refrigerant flow (VRF) HVAC system, vertical stack optimization plays a crucial role. The VRF system is designed to serve multiple zones vertically, and improper stack design can lead to inefficiencies, uneven temperature distribution, and increased energy consumption.

Engineers first consider the load characteristics of different floors. For example, the lower floors may have more traffic and thus higher heat loads due to people's activities. By accurately assessing these loads, they can group zones with similar load requirements vertically. This ensures that the refrigerant flow can be better regulated, minimizing the situation where some zones are over cooled or under cooled.

Secondly, the length of refrigerant pipes in the vertical stack is optimized. Long pipes can cause pressure drops, reducing the system's performance. To address this, the vertical layout is carefully planned to keep the pipe lengths as short as possible while still meeting the building's architectural and functional requirements. This may involve strategic placement of outdoor units on certain floors to shorten the connection lengths to indoor units.

Moreover, the impact of elevation differences on the VRF system is also taken into account. Large elevation differences can affect the refrigerant circulation. Through proper design of the vertical stack, such as using appropriate refrigerant management devices at different levels, the system can operate more stably. Overall, through these vertical stack optimization measures in the high-density residential project, the VRF HVAC system can achieve better performance, energy efficiency, and indoor comfort, as supported by relevant research [10].

5.1.2. Noise mitigation achievements

In the high-density residential project, significant noise mitigation achievements were made through the implementation of vibration isolators and duct silencers in the HVAC engineering. After the installation of these noise reducing devices, a comprehensive measurement of the acoustic environment was carried out. The results showed a remarkable reduction in decibels (dB).

Vibration isolators were installed at key points where the HVAC equipment was in contact with the building structure. These isolators effectively absorbed and dampened the vibrations generated by the operation of the equipment, preventing them from being transmitted to the building structure and causing noise pollution. For example, at the base of the large capacity air handling units, the vibration isolators reduced the structural borne noise significantly.

Duct silencers, on the other hand, were installed within the ductwork. They were designed to attenuate the noise generated by the air flowing through the ducts. By altering the acoustic properties of the air flow path, the duct silencers were able to reduce the airborne noise.

Quantitative measurements indicate that, on average, the installation of vibration isolators reduces the sound transmission of the structure by decibels, while pipeline mufflers reduce the sound transmission of the air by decibels. These improvements not only met the acoustic requirements of the high density residential project but also enhanced the living comfort of the residents, demonstrating the effectiveness of these noise mitigation measures in HVAC engineering construction management [11].

5.2. Mixed-use development

5.2.1. Thermal load balancing

In a mixed-use development project, demand-controlled ventilation algorithms play a crucial role in thermal load balancing for simultaneous retail/residential space conditioning. Consider a large-scale mixed-use building with multiple retail floors at the bottom and residential apartments above [12].

The retail areas usually have high density human occupancy during business hours, resulting in significant heat generation from people, lighting, and equipment. In contrast, residential spaces have more variable occupancy patterns. To balance the thermal loads, the demand-controlled ventilation system continuously monitors factors such as indoor temperature, humidity, and carbon dioxide levels in both retail and residential zones.

For the retail spaces, when the system detects a rise in temperature or an increase in carbon dioxide concentration due to high customer traffic, it ramps up the ventilation rate. This not only provides fresh air but also helps dissipate the heat generated. In the residential areas, the system adjusts the ventilation based on the occupancy sensors. If an apartment is unoccupied, the ventilation rate is reduced to save energy.

By accurately regulating the ventilation in different zones according to their real time demands, the HVAC system can effectively balance the thermal loads between the retail and residential spaces. This approach not only improves the indoor comfort for both retailers and residents but also optimizes energy consumption, which is a key aspect in the construction management of HVAC engineering in real estate projects.

5.2.2. Commissioning workflow enhancements

In the implementation case studies of mixed-use development in the construction management of HVAC engineering in real estate, the commissioning workflow enhancements are of great significance. Take the situation of achieving a 30% schedule compression using automated testing–adjusting–balancing (TAB) procedures [13]. In a certain large scale mixed use real estate project, traditional commissioning methods often led to time consuming and labor-intensive processes. However, by introducing automated TAB procedures, a series of improvements were made.

Automated TAB systems can quickly and accurately measure and adjust the air volume, water flow, and other parameters of the HVAC system. This not only improves the precision of commissioning but also greatly accelerates the workflow. For example, in the past, manual inspection and adjustment of each air handling unit might take hours or even days, but with the automated system, it can be completed within a much shorter time frame.

The data collected by the automated TAB procedures can be analyzed in real time, enabling commissioning engineers to promptly identify and address potential problems. This proactive approach reduces the rework and debugging time during the commissioning phase. Moreover, the automated system provides detailed and standardized reports, which are beneficial for quality control documentation and future system maintenance. Overall, through the application of automated TAB procedures in the commissioning workflow of mixed-use development projects, significant schedule compression and quality control improvements have been achieved in HVAC engineering construction management.

5.3. Retrofitting historical structures

5.3.1. Heritage compliance solutions

This case study showcases the adaptation of micro channel heat exchanger in preservation sensitive installations, specifically in historical structures. When retrofitting historical real estate for HVAC systems, there are strict heritage compliance requirements.

In this instance, the historical building had unique architectural features and a rich cultural background that needed to be preserved. The use of a micro channel heat exchanger was a strategic choice. It has a compact design, which allows for installation in limited spaces without causing significant damage to the original structure. This is crucial as any major structural alteration could violate heritage regulations [14].

Moreover, the micro channel heat exchanger is energy efficient. In historical structures, energy conservation measures are often encouraged to reduce the overall environmental impact while also being in line with modern sustainability goals. The installation process was carefully planned. Special care was taken to ensure that the installation methods did not harm the building's historical fabric. For example, instead of making large scale penetrations in the walls, the heat exchanger was installed in a way that utilized existing openings or spaces in the building's infrastructure. This not only adhered to heritage compliance but also minimized the disruption to the building's aesthetic and historical integrity. The successful implementation of the micro channel heat exchanger in this historical structure serves as an example of how HVAC engineering in real estate can be managed to meet both quality control standards and heritage requirements.

5.3.2. Energy recovery innovations

In the retrofitting of historical structures, a significant innovation in energy recovery was the application of enthalpy wheels. This case study validates the remarkable efficiency of enthalpy wheels in the context of HVAC engineering for real estate construction management.

The enthalpy wheels play a dual role. Firstly, they are highly effective in maintaining Indoor Air Quality (IAQ). In historical structures, preserving a healthy and comfortable indoor environment is crucial, especially considering the potential limitations in natural ventilation due to the building's heritage protected status. The enthalpy wheels ensure that fresh air is introduced while removing stale air, adhering to strict IAQ standards.

Secondly, they have a substantial impact on reducing mechanical cooling loads. By pre conditioning the incoming fresh air using the energy from the exhaust air, the enthalpy wheels manage to cut down mechanical cooling loads by as much as 42%. This not only leads to significant energy savings but also eases the burden on the HVAC system. In historical buildings, where space for installing large scale cooling equipment might be restricted, this reduction in cooling load is a game changer. It allows for the selection of more compact and energy efficient cooling units, which are more in line with the building's aesthetic and spatial constraints. Overall, the use of enthalpy wheels in the retrofitting of historical structures represents a key strategy in HVAC engineering for real estate, achieving both quality control in terms of IAQ and energy efficient operation.

6. Conclusion

In conclusion, this study on the construction management of HVAC engineering in real estate has illuminated three crucial strategic dimensions for effective quality control. Predictive design validation serves as the cornerstone, enabling project teams to anticipate and rectify potential design flaws before construction commences, thus preventing costly rework. Digitized construction monitoring, on the other hand, provides real time insights into the construction process, ensuring that any deviations from the plan can be promptly addressed. Adaptive commissioning, the final piece of the puzzle, fine tunes the HVAC system to its optimal performance, guaranteeing long term efficiency and functionality.

The proposed 5 phase quality maturity model for HVAC project teams has proven to be a practical and effective tool. In case implementations, it has not only achieved a significant 28% reduction in defects but also maintained an impressive 98% schedule adherence. This model can be a guiding framework for other real estate

HVAC projects, facilitating continuous improvement in quality management.

Going forward, the real estate industry should further embrace these strategies and the quality maturity model. By doing so, they can enhance the overall quality of HVAC systems, leading to increased customer satisfaction, reduced operational costs, and a more sustainable built environment. Future research could explore the integration of emerging technologies, such as artificial intelligence and the Internet of Things, into these strategies to further optimize the construction management of HVAC engineering in real estate.

Disclosure statement

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Analysis of Key Technologies for On-site Detection of Subgrade and Pavement of Municipal Roads

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Abstract: On-site inspection of municipal road subgrade and pavement is of great significance for ensuring the quality, safety, and durability of urban road infrastructure. This paper analyzes its key technologies, introduces non-destructive testing methods such as ground-penetrating radar and ultrasonic testing, elaborates on the multifaceted roles of inspection in engineering construction as well as relevant standards, explores site challenges, key technologies, and corresponding measures, and points out future research directions in intelligent sensing and predictive maintenance.

Keywords: Municipal roads; Subgrade and pavement inspection; Key technologies

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1. Introduction

The on-site detection of municipal road subgrade and pavement is essential for ensuring the quality, safety, and durability of urban road infrastructure. With the continuous development of urbanization, the importance of accurate detection technologies has become even more prominent. In recent years, relevant policies have been introduced to support the development of this field. For example, the “Urban Road Infrastructure Construction and Maintenance Guidelines” emphasizes the need to improve the level of on-site detection of subgrade and pavement to enhance the overall quality of urban roads. Advances in non-destructive testing technologies, as highlighted in recent research, further underscore the progress in this area [1]. This paper delves into the key detection technologies, analyzes the challenges faced, and explores future research directions, aiming to contribute to the sustainable development of urban road construction.

2. Overview of municipal road subgrade and pavement detection

2.1. Core detection technologies

Ground penetrating radar (GPR) is a widely used technology in the on-site detection of municipal road subgrade and pavement. It works by emitting electromagnetic waves into the ground and analyzing the reflected waves to identify subsurface structures, voids, or thickness changes in the subgrade and pavement layers. GPR can provide high resolution images of the internal structure of the road, helping engineers accurately assess the integrity of the roadbed and pavement [2].

Ultrasonic testing is another important nondestructive testing method. Ultrasonic waves are transmitted through the road materials, and the time of flight and amplitude of the waves are measured. By analyzing these parameters, information about the internal structure, such as cracks, porosity, and layer interfaces, can be obtained. This method is effective in detecting small scale defects and changes in material properties within the subgrade and pavement.

These nondestructive testing methods play a crucial role in on-site detection of municipal road subgrade and pavement. They allow for a quick and accurate assessment of the structural integrity without causing damage to the road surface, which is essential for timely maintenance and repair of municipal roads, ensuring their long-term serviceability and safety.

2.2. Role in construction engineering

The detection of municipal road subgrade and pavement plays a pivotal and multi-faceted role in construction engineering. Firstly, it serves as a quality gatekeeper. By accurately assessing the physical and mechanical properties of the subgrade, such as soil compaction degree and bearing capacity, and the performance of the pavement like thickness and flatness, it ensures that the road construction meets the predefined quality standards. Faulty subgrade or pavement can lead to premature road failures, affecting traffic safety and durability [3].

Secondly, the detection helps in cost control. Early detection of potential problems allows for timely adjustments and rectifications during the construction process. For example, if the subgrade is not compacted properly, discovering this issue early can prevent the need for costly reconstruction later on, which would involve removing and rebuilding a large section of the road.

Thirdly, it contributes to environmental protection in construction. By detecting the quality of materials used in the subgrade and pavement, it can ensure that no harmful substances are released during construction or in the long-term service life of the road. This is in line with the sustainable development requirements of modern construction engineering.

In summary, the on-site detection of municipal road subgrade and pavement is an essential link in construction engineering, safeguarding quality, cost, and environmental friendliness simultaneously.

3. Detection requirements and standards

3.1. Municipal engineering specifications

In municipal engineering specifications, when it comes to on-site detection of subgrade and pavement of municipal roads, the comparison of technical requirements among different standards is crucial. ASTM (American Society for Testing and Materials) and AASHTO (American Association of State Highway and Transportation Officials) standards have their own characteristics in road compaction, bearing capacity, and layer thickness measurements. For example, in road compaction testing, ASTM may emphasize certain test procedures and equipment specifications to accurately measure the degree of compaction. AASHTO might focus more on the relationship between compaction and traffic load bearing capacity.

On the other hand, Chinese GB (Guobiao, national standards) also has its own set of strict requirements. In road compaction, Chinese standards not only consider the basic physical properties of the soil or materials but also take into account the long-term stability and durability of the road under local climate and traffic conditions. For bearing capacity testing, Chinese GB standards are designed to ensure that the subgrade and pavement can withstand the expected traffic loads during their service life. Regarding layer thickness measurements, precise methods are specified to guarantee the proper structure and performance of each road layer. By comparing these standards, engineers can select the most suitable detection methods and ensure the quality of municipal road construction, taking into account both international best practices and local engineering needs [4].

3.2. Site-specific challenges

Urban traffic presents significant constraints for on-site detection of subgrade and pavement in municipal roads. The high volume of vehicles in urban areas makes it difficult to conduct continuous and comprehensive detection. For example, in peak traffic hours, the detection equipment may not be able to operate freely, leading to interrupted data collection, which in turn affects the accuracy and integrity of the detection results [5].

Underground utility interference is another crucial challenge. Municipal roads are often criss crossed with various underground utilities such as water pipes, gas pipelines, and power cables. These utilities can interfere with the detection signals of subgrade and pavement, causing false readings or inaccurate data. For instance, electromagnetic signals from power cables can disrupt the electromagnetic based detection methods used to assess the subgrade condition.

Environmental factors also play a role in influencing detection accuracy. Weather conditions like heavy rain, snow, or extreme heat can impact the performance of detection equipment. High humidity may cause corrosion of sensors, while extreme temperatures can affect the physical properties of the detection materials, leading to inaccurate measurements. In addition, urban dust and pollution can accumulate on the detection equipment, potentially reducing its sensitivity and reliability. All these site-specific challenges need to be carefully considered and addressed to ensure accurate and effective on-site detection of subgrade and pavement in municipal roads.

4. Critical technology analysis

4.1. Non-destructive evaluation

4.1.1. GPR applications

Ground Penetrating Radar (GPR) is a crucial nondestructive evaluation tool in the on-site detection of subgrade and pavement of municipal roads. It operates based on the principle of electromagnetic wave reflection analysis. When GPR emits electromagnetic waves into the subgrade and pavement structures, the waves travel through different materials. The dielectric properties of various substances within the structures, such as voids, different soil types, and pavement layers, are distinct, causing the electromagnetic waves to reflect at the interfaces between these materials.

For void detection, the reflected waves from voids show characteristic patterns. The amplitude and travel time of the reflected waves can be analyzed to determine the presence, location, and approximate size of voids. A sudden change in the reflection signal indicates a potential void area [6]. In terms of density profiling, the propagation speed of electromagnetic waves is related to the density of the medium. Denser materials generally cause the waves to travel more slowly. By measuring the travel time of the waves through different layers and analyzing the reflection signals, engineers can estimate the density distribution within the subgrade and pavement. This information is vital for assessing the quality and integrity of the road structures, helping to identify areas that may be prone to future damage or settlement, and guiding appropriate maintenance and repair strategies.

4.1.2. Ultrasonic pulse velocity

Ultrasonic Pulse Velocity (UPV) is a crucial nondestructive evaluation technique for on-site detection of subgrade and pavement of municipal roads. In the context of municipal pavement quality control, it can be effectively used to assess the homogeneity of concrete.

When using UPV, ultrasonic waves are transmitted through the concrete structure of the pavement. The velocity of these ultrasonic pulses depends on various factors such as the density, elasticity, and internal structure of the concrete. Homogeneous concrete will allow the ultrasonic waves to travel at a relatively consistent velocity. By analyzing the waveforms of the received ultrasonic signals, engineers can gain insights into the internal condition of the pavement [7].

If there are voids, cracks, or inhomogeneous material distributions within the concrete, the ultrasonic pulse velocity will change. For example, a lower-than-normal velocity may indicate the presence of a void or a crack, as the wave has to travel through a less dense medium or a disrupted path. On the other hand, an abnormal increase in velocity might suggest a region of higher density or more compacted concrete.

The UPV method offers several advantages for on - site detection. It is nondestructive, meaning it does not cause damage to the pavement structure, allowing for continuous monitoring over time. It is also relatively quick and can provide real - time results, enabling prompt decision making during the construction or maintenance of municipal roads. This technique, therefore, plays an essential role in ensuring the quality and integrity of subgrade and pavement in municipal road projects.

4.2. Destructive testing methods

4.2.1. Dynamic cone penetrometer

The dynamic cone penetrometer is a crucial tool in destructive testing methods for on-site detection of subgrade and pavement of municipal roads. It can rapidly and effectively evaluate the strength characteristics of subgrade materials.

This device operates by driving a cone shaped penetrator into the soil under dynamic impact. The resistance encountered during penetration is related to the strength properties of the soil. The measured penetration resistance can be used to estimate parameters such as the California Bearing Ratio (CBR) of the subgrade, which is essential for assessing the load bearing capacity of the subgrade.

When using the dynamic cone penetrometer, factors like the mass of the falling weight, the height of the drop, and the cone angle need to be precisely controlled. These parameters directly influence the penetration resistance values obtained. The testing procedure typically involves multiple penetration measurements at different locations within the test area to ensure the representativeness of the results.

Compared with some traditional static testing methods, the dynamic cone penetrometer offers the advantage of quick operation, which is beneficial for large scale on-site inspections. However, it also has limitations. For example, the results may be affected by soil heterogeneity and the presence of gravel or other inclusions in the soil. To overcome these limitations, it is often necessary to combine the results of dynamic cone penetrometer tests with other testing methods. In conclusion, the dynamic cone penetrometer plays an important role in the on-site detection of subgrade and pavement, but its application should be carefully considered in light of the specific characteristics of the test site [8].

4.2.2. Core sampling analysis

Core Sampling Analysis involves carefully extracting cylindrical samples from the subgrade and pavement. This method is crucial as it provides direct access to the internal structure and composition of the materials. For the subgrade, cores are taken to determine its density, moisture content, and soil particle distribution. By analyzing these parameters, engineers can assess the subgrade's load bearing capacity and stability. In the case of the pavement, especially asphalt pavement, core sampling helps in verifying the thickness of different layers, such as the asphalt layer, base layer, and sub base layer. It also allows for the examination of the asphalt aggregate ratio and the quality of compaction.

Laboratory tests are then carried out on these core samples. For density measurement, methods like the wax sealing method or the core cutter method can be used. To determine the moisture content, samples are dried in an oven at a specific temperature until a constant weight is achieved. The analysis of aggregate gradation in the asphalt mixture from the core samples follows standard sieve analysis procedures. Through these detailed laboratory tests on core samples, accurate data can be obtained to evaluate the quality and performance of the subgrade and pavement, ensuring that they meet the design requirements and can withstand the long-term traffic loads and environmental impacts [9].

5. Technological challenges and solutions

5.1. Environmental limitations

5.1.1. Moisture interference mitigation

Moisture interference is a significant challenge in the on-site detection of subgrade and pavement of municipal roads. Groundwater and surface moisture can greatly affect the accuracy of detection results, especially in dielectric constant measurements. For example, moisture can change the electrical properties of subgrade and pavement materials, leading to inaccurate readings of dielectric-based detection methods.

To mitigate this moisture interference, multi sensor fusion approaches are proposed [10]. By integrating data from multiple sensors, such as dielectric sensors, resistivity sensors, and moisture specific sensors, a more comprehensive understanding of the moisture condition can be achieved. Dielectric sensors can provide information about the dielectric properties of the materials, which are related to moisture content. Resistivity sensors, on the other hand, can measure the electrical resistivity of the materials, which also varies with moisture levels. Combining these two types of sensors can help cross validate the moisture information. Additionally, moisture specific sensors can directly detect the presence and amount of moisture in the materials. The fusion of data from these different sensors can reduce the uncertainty caused by moisture interference. Through data fusion algorithms, the complementary information from each sensor is integrated, enabling more accurate determination of the subgrade and pavement conditions, even in the presence of moisture. This approach improves the reliability and precision of on-site detection, ensuring that the results can better reflect the real-world state of the municipal road subgrade and pavement.

5.1.2. Temperature compensation models

Developing accurate temperature compensation models is crucial for the on-site detection of subgrade and pavement of municipal roads, especially in seasonal pavement monitoring. Temperature variations can significantly affect the performance and measurement results of detection technologies. For example, in cold seasons, materials contract, while in hot seasons, they expand, potentially leading to inaccurate readings of pavement thickness, subsidence, or crack widths.

To address this, algorithms for thermal expansion correction are developed. These algorithms take into account the physical properties of pavement materials, such as their coefficient of thermal expansion. By accurately measuring the ambient temperature during on-site detection and using the established thermal expansion models, the raw measurement data can be adjusted. For instance, if the measured crack width seems larger in a hot environment, the algorithm can correct this value based on the known thermal expansion characteristics of the pavement material [11].

The temperature compensation models also need to consider the time dependent effects of temperature changes. The rate at which the pavement material responds to temperature variations can vary, and this dynamic behavior must be incorporated into the model. Additionally, different layers of the subgrade and pavement may have different temperature related responses. By comprehensively analyzing these factors and refining the temperature compensation models, more accurate and reliable on-site detection results can be obtained, enabling better assessment of the health and condition of municipal road subgrades and pavements.

5.2. Equipment optimization

5.2.1. Portable detection systems

Portable detection systems play a crucial role in on-site detection of subgrade and pavement of municipal roads. These systems face several technological challenges. One significant issue is achieving high precision data collection in a portable form factor. The limited space and power supply in portable devices restrict the installation of large-scale, high-performance sensors. To address this, integrated sensor platforms with edge computing capabilities are developed [12]. These platforms can process data in real time at the edge of the network, reducing the need for large scale data transfer to a central server. By integrating multiple types of sensors, such as ground penetrating radar sensors for subgrade structure detection and optical sensors for pavement surface condition monitoring, into a compact and portable unit, more comprehensive data can be collected. Moreover, the edge computing function enables immediate data analysis, providing quick feedback on potential problems like subgrade voids or pavement cracks. This not only improves the efficiency of on-site detection but also ensures that timely measures can be taken to maintain the quality of municipal road subgrades and pavements. Additionally, the portability of these systems allows for easy access to various road sections, including those in hard-to-reach areas, which is essential for comprehensive road condition assessment.

5.2.2. Automated interpretation software

Automated interpretation software plays a crucial role in on-site detection of subgrade and pavement of municipal roads. One of the main technological challenges lies in accurately recognizing complex signal patterns in the data collected from various detection equipment. Traditional methods often rely heavily on operators' experience and manual interpretation, which not only consumes a great deal of time but also has high subjectivity, leading to inconsistent results [13].

To address this, machine learning based automated interpretation software has emerged. By training on a large number of labeled data, the software can learn the characteristics of different signal patterns related to subgrade and pavement conditions. For example, it can distinguish between normal and abnormal signals indicating issues like cracks, voids, or unevenness. This significantly reduces the dependency on individual operators' skills and knowledge.

Moreover, the software can be designed to adapt to different types of detection equipment and data formats. It can preprocess the raw data, remove noise and standardize the data structure to ensure better pattern recognition. Additionally, real time processing capabilities are integrated into the software, enabling immediate feedback during on-site detection. This allows engineers to take timely measures, improving the efficiency and accuracy of the entire detection process for municipal road subgrades and pavements.

5.3. Data integration strategies

5.3.1. BIM-GIS convergence

In the context of on-site detection of subgrade and pavement of municipal roads, the convergence of Building Information Modeling (BIM) and Geographic Information System (GIS) faces several technological challenges. BIM mainly focuses on the detailed 3D modeling of buildings and structures, while GIS emphasizes spatial analysis and geographical data management. Integrating these two systems requires resolving differences in data formats, data granularity, and data storage mechanisms. For example, BIM data is often in a proprietary format with high level details for construction elements, while GIS data is more general - purpose and suitable for large scale spatial analysis.

To address these challenges, one solution is to develop unified data standards. By establishing common data models and exchange formats, seamless data transfer between BIM and GIS can be achieved. Another approach is to use middleware or conversion tools. These can act as bridges to translate BIM data into a format that GIS can understand and vice versa. Additionally, semantic integration is crucial. This involves mapping the semantics of BIM elements to GIS features, enabling more meaningful data integration. For instance, a road segment in BIM can be semantically linked to a corresponding linear feature in GIS for better spatial analysis and lifecycle management of municipal road infrastructure [14]. Through these strategies, the BIM - GIS convergence can be effectively realized, providing a more comprehensive and powerful platform for on-site detection and management of municipal road subgrade and pavement.

5.3.2. Multi-temporal analysis frameworks

Multi-temporal analysis frameworks play a crucial role in accurately predicting the pavement deterioration trend through the establishment of time series evaluation systems. One of the main technological challenges lies in handling the vast amount of multi - temporal data collected from various sources during the on-site detection of subgrade and pavement of municipal roads. These data may come from different sensors, survey methods, and time intervals, which can lead to issues such as data heterogeneity and inconsistent data formats.

To address these challenges, effective data integration strategies are essential. For example, a standardized data format should be defined for all data sources related to multi temporal analysis. This ensures that data can be easily combined and analyzed. Additionally, advanced algorithms can be utilized to preprocess the data, removing noise and outliers while normalizing different data types.

In terms of the multitemporal analysis frameworks themselves, a hierarchical model can be adopted. At the lower level, detailed data from each detection time point is analyzed to identify short term changes and anomalies. At the higher-level, long-term trends are extracted by integrating data over multiple time points. This hierarchical approach helps in both detecting immediate problems and predicting long term pavement deterioration trends, enabling more comprehensive and accurate evaluation of the subgrade and pavement conditions of municipal roads.

6. Conclusion

In conclusion, the analysis of key technologies for on-site detection of subgrade and pavement of municipal roads has illuminated significant aspects of modern urban infrastructure management. The technological advances in this field, as discussed, have enabled more accurate, efficient, and nondestructive ways to assess the condition of subgrades and pavements. These advancements not only contribute to maintaining the structural integrity of municipal roads but also enhance the overall safety and durability of the transportation network.

The proposed implementation roadmaps for construction quality assurance serve as practical guidelines for construction teams and relevant authorities. By adhering to these roadmaps, it is possible to ensure that new construction and maintenance projects meet high quality standards, thereby reducing the long-term cost of road management.

Looking ahead, the future research directions in smart sensing and predictive maintenance systems hold great promise. Smart sensing technologies can provide real time data on road conditions, enabling proactive measures to be taken before serious damage occurs. Predictive maintenance systems, on the other hand, can optimize maintenance schedules based on data driven models, leading to more efficient use of resources. Overall, continuous research and innovation in these areas will be crucial for the sustainable development of municipal road infrastructure, ensuring that it can meet the growing demands of urbanization and modern transportation.

Disclosure statement

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Discussion on the Design and Optimization Strategy of Automatic Sprinkler Fire Extinguishing in Building Fire Protection Systems

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Abstract: This paper focused on the design and optimization of automatic sprinkler fire extinguishing systems in building fire protection. It was emphasized the importance of considering various factors in design, such as fire risk assessment and space utilization. Optimization strategies include enhancing water and energy efficiency, using ecofriendly materials, and smart monitoring. Practical implementation and validation in different building types were presented, along with performance benchmark analysis. Balancing fire safety and resource utilization is crucial, and future research in AI driven tuning and nano materials was promising.

Keywords: Automatic sprinkler system; Optimization strategy; Building fire protection

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1. Introduction

In the domain of building fire protection, the automatic sprinkler fire extinguishing system is of great significance. As buildings become more intricate and diverse, fire risks escalate. To ensure the optimal functioning of this system, a comprehensive understanding of multiple factors and the implementation of optimization strategies are essential. In 2021, the "National Fire Protection Regulations" was promulgated, emphasizing the importance of building fire protection systems. This paper delves into the design and optimization of the automatic sprinkler fire extinguishing system, covering aspects like configuration principles, hydraulic calculation, multi objective optimization, and smart monitoring [1]. It aims to offer valuable insights for professionals, enhance building fire safety, and align with the requirements of the latest fire protection policy.

2. Fundamentals of automatic sprinkler system design

2.1. Core principles of fire protection system configuration

The core principles of fire protection system configuration in the design of automatic sprinkler systems are of utmost importance. Fire risk assessment in civil and industrial buildings serves as the foundation. It was necessary to accurately evaluate the potential fire hazards, considering factors such as the type of occupancy, the materials used in construction, and the presence of flammable substances. This assessment was used to determine the appropriate level of fire protection required [2].

Space utilization requirements also play a crucial role. The layout of the sprinkler system was designed to ensure comprehensive coverage while minimizing interference with normal activities in the building. For instance, in industrial facilities with large machinery, the sprinklers need to be positioned in a way that they can effectively reach all potential fire sources without obstructing the operation of the equipment. In civil buildings like offices or residential units, the sprinkler layout should blend in with the interior design and not cause inconvenience to the occupants.

By integrating fire risk assessment and space utilization requirements, a rational design framework for sprinkler layouts were established. This framework guides the determination of the number, type, and location of sprinklers, ensuring that the automatic sprinkler system can function optimally to suppress fires promptly and protect the safety of people and property within the building.

2.2. Hydraulic calculation methodology

Hydraulic calculation in the design of automatic sprinkler systems was crucial for ensuring their effective performance. According to NFPA 13 standards and considering building occupancy characteristics, a proper methodology was required to be adopted. The process typically involves determining the flow rate required for each sprinkler based on factors such as the type of occupancy, hazard classification, and sprinkler spacing. For different building occupancies, like light, ordinary, or high hazard areas, the design criteria vary significantly.

The flow pressure relationship was calculated to ensure that each sprinkler received the appropriate amount of water at the correct pressure. This requires considering the friction losses in the pipes, elevation differences within the building, and the available water supply pressure. Computational methods were used, with algorithms that can simulate the flow distribution in the pipe network. These algorithms help in optimizing the pipe network topology to achieve flow pressure balance. By using such hydraulic calculation methodology, designers can ensure that the automatic sprinkler system functions as intended, providing reliable fire protection for the building and its occupants [3]. It enables the accurate sizing of pipes, selection of appropriate pumps, and determination of the overall system layout to meet the firefighting requirements effectively.

3. Multi-objective optimization strategies

3.1. Water efficiency enhancement approaches

To enhance water efficiency in the automatic sprinkler fire extinguishing systems of building fire protection, two key approaches can be implemented: variable flow sprinkler technology and reclaimed water utilization mechanisms.

Variable flow sprinkler technology allows for the adjustment of water flow based on the intensity of the fire. In the initial stages of a fire, when the scale was relatively small, the sprinklers can operate with a lower water flow rate, which was sufficient to control the fire spread. As the fire intensifies, the flow rate was then increased accordingly. This not only ensures effective firefighting but also significantly reduced unnecessary water consumption during less severe fire situations [4].

The utilization of reclaimed water mechanisms was another important aspect. Reclaimed water, which has been treated to meet certain quality standards, can be sourced from sources such as treated sewage or rainwater collected from the building’s roof. By using reclaimed water in the sprinkler systems, the demand for fresh water can be greatly decreased. However, it was crucial to ensure that the reclaimed water does not cause any damage to the sprinkler components, such as corrosion or blockage. Therefore, appropriate water treatment and monitoring processes need to be in place to guarantee the long-term performance and reliability of the system. These two approaches combined can effectively minimize water consumption while maintaining the necessary firefighting capacity in building fire protection systems.

3.2. Energy-smart system integration

Developing pump frequency conversion control strategies and thermal load responsive activation protocols is crucial for reducing energy expenditure in automatic sprinkler fire extinguishing systems within building fire protection setups. Pump frequency-conversion control can adjust the pump's operating speed according to the actual water demand. In a non-fire situation or when the fire scale is small, the pump can operate at a lower speed, consuming less energy. This not only helps in energy conservation but also extends the service life of the pump and related equipment.

Thermal load responsive activation protocols, on the other hand, ensure that the sprinkler system activates precisely when necessary. By accurately detecting the thermal load in the building environment, the system can start the sprinklers only in areas where there is a real fire threat. This prevents unnecessary activation of the entire system, thus reducing water and energy waste.

For example, advanced sensors were installed throughout the building to monitor temperature changes and heat fluxes. These sensors can communicate with a central control unit that is programmed to analyze the data and make decisions regarding the activation of the sprinkler system. This integration of smart control strategies based on pump frequency conversion and thermal load responsiveness can achieve multi objective optimization, including energy saving, efficient firefighting, and cost effectiveness in building fire protection systems [5].

4. Green building compliance and innovation

4.1. Sustainable material applications

4.1.1. Eco-friendly pipe materials

In the context of green building compliance and innovation, the application of ecofriendly pipe materials in automatic sprinkler fire extinguishing systems was of great significance. When evaluating corrosion resistant composite materials for these systems, it was essential to consider their lifecycle environmental impacts [6].

Firstly, corrosion resistant composite pipe materials can offer enhanced durability, reducing the need for frequent replacements. This not only cuts down on material waste but also decreases the energy consumption associated with production and installation. For instance, some composite pipes made from recycled polymers can maintain their structural integrity and firefighting performance over a long period.

Secondly, the environmental impact throughout the lifecycle of these materials must be carefully analyzed. The extraction of raw materials, the manufacturing process, the transportation to the construction site, and the end-of-life disposal all contribute to the overall environmental footprint. Materials with low energy manufacturing processes and high recyclability are more favorable. For example, certain composite pipes can be easily recycled at the end of their service life, minimizing the amount of waste sent to landfills.

Furthermore, ecofriendly pipe materials should also meet the strict performance requirements of automatic sprinkler systems. They need to withstand high water pressures, resist chemical corrosion from water additives, and maintain their fire-resistant properties. Only by ensuring both environmental friendliness and high performance can these materials truly contribute to the sustainable development of building fire protection systems while adhering to green building compliance standards.

4.1.2. Recyclable component design

Developing modular sprinkler assemblies with disassembly friendly connections is crucial for recyclable component design in the context of green building compliance and innovation. By creating modular designs, each part of the sprinkler assembly can be easily separated. This not only simplifies the repair process but also significantly enhances recyclability. When a component fails, instead of discarding the entire sprinkler unit, only the faulty module needs to be replaced.

The use of disassembly friendly connections, such as quick release couplings or snap fit mechanisms, enables easy separation of different components. These connections should be designed to withstand the operational pressures within the automatic sprinkler system while still allowing for disassembly without causing damage to the parts. This way, at the end of life of the sprinkler system, the components can be efficiently sorted and recycled.

For instance, the metal parts of the modular sprinkler can be melted down and reused in the production of new sprinkler components or other metal products. The plastic components, if made from recyclable polymers, can also be processed and remolded into new plastic parts. This approach aligns with the principles of the circular economy, reducing waste and conserving resources. Overall, such recyclable component design in automatic sprinkler systems is an important step towards sustainable building fire protection and green building compliance [7].

4.2. Smart monitoring integration

4.2.1. IoT-enabled leakage detection

IoT Enabled Leakage Detection is a crucial aspect in the smart monitoring integration for automatic sprinkler fire extinguishing systems within building fire protection. By leveraging the power of the Internet of Things (IoT), highly sensitive sensors can be deployed throughout the pipeline network of the sprinkler system. These sensors are designed to detect even the slightest signs of leakage, which could otherwise go unnoticed and lead to system inefficiencies or complete failures during a fire emergency [8].

The IoT enabled sensors operate by constantly monitoring parameters such as water pressure, flow rate, and vibration patterns within the pipes. A sudden drop in pressure or an abnormal change in flow rate could indicate a potential leakage point. Vibration sensors can also detect the unique patterns associated with water escaping from the pipeline. Once a potential leakage is detected, the sensor immediately sends a real time alert to a central monitoring station. This allows maintenance crews to respond promptly, minimizing water damage to the building and ensuring the integrity of the fire extinguishing system.

Moreover, the data collected by these IoT sensors can be analyzed over time to predict potential leakage locations. Through advanced analytics, trends in pressure changes and flow irregularities can be identified, enabling proactive maintenance. For example, if a particular section of the pipeline consistently shows minor pressure fluctuations, it can be flagged for further inspection before a full-blown leak occurs. This not only improves the reliability of the automatic sprinkler system but also aligns with the principles of green building compliance by reducing water waste and preventing unnecessary damage to the building structure.

4.2.2. BIM-based maintenance systems

Building Information Modeling (BIM) technology offers a revolutionary approach to the maintenance of automatic sprinkler fire extinguishing systems in building fire protection. By creating digital twins of sprinkler systems, it enables more precise and efficient maintenance scheduling.

With BIM, all relevant information about the sprinkler system, such as the type, location, and installation date of each component, can be integrated into a single digital model. This comprehensive database allows maintenance personnel to quickly access and analyze data, facilitating a better understanding of the system's overall condition. For example, when a component approaches its expected service life, the BIM based system can send out alerts, enabling proactive maintenance.

Moreover, BIM based maintenance systems can simulate the performance of the sprinkler system under different scenarios. This helps in predicting potential failures and developing preventive measures. By running virtual tests on the digital twin, maintenance teams can optimize the maintenance plan, ensuring that resources are allocated effectively. For instance, they can determine the most appropriate time to replace a part to minimize system downtime and cost. In addition, the digital twin can be used to train new maintenance staff, providing them with a realistic and safe environment to practice maintenance procedures. Overall, BIM based maintenance systems enhance the maintenance efficiency and reliability of automatic sprinkler fire extinguishing systems, making a significant contribution to building fire protection [9].

5. Practical implementation and validation

5.1. Industrial building case studies

5.1.1. High-risk manufacturing facility retrofit

In the retrofit of high-risk manufacturing facilities, practical implementation and validation play a crucial role in demonstrating water consumption reduction through optimized nozzle configurations and pressure zoning in automatic sprinkler fire extinguishing systems.

Firstly, for the practical implementation, detailed on-site surveys are carried out in high-risk manufacturing facilities such as chemical plants. This includes mapping out the layout of production areas, storage locations of hazardous substances, and existing firefighting infrastructure. Based on this information, engineers design optimized nozzle configurations. For example, in areas with higher fire risks, like where highly flammable chemicals are stored, nozzles with a higher discharge rate and a wider spray angle are installed. These nozzles are carefully spaced to ensure comprehensive fire coverage.

Regarding pressure zoning, the facility was divided into different zones according to the fire risk levels and the height of the building. High risk areas may be in a separate high-pressure zone, while relatively low risk areas were in a lower pressure zone. This zoning was achieved through the installation of pressure regulating valves and appropriate pipe sizing.

After implementation, validation is essential. Firefighting performance tests are conducted in the retrofitted high risk manufacturing facility. These tests simulate different fire scenarios, such as small-scale chemical spills catching fire. Water consumption data is collected during the tests. By comparing the water consumption in the optimized system with the previous unoptimized system, the effectiveness of the optimized nozzle configurations and pressure zoning can be clearly demonstrated. If the water consumption is significantly reduced while still ensuring effective fire suppression, it validates the retrofit strategy, which can serve as a reference for other similar high risk manufacturing facilities [10].

5.1.2. Warehouse protection system upgrade

In the upgrade of the warehouse protection system, the implementation of early suppression fast response (ESFR) technology with energy recovery mechanisms was crucial. First, in terms of practical implementation, the layout of ESFR sprinklers needs to be carefully designed. According to the size, height, and storage type of the warehouse, the appropriate number and spacing of sprinklers were determined. For example, in a large-scale high rack warehouse storing combustible goods, more sprinklers may be required at closer intervals compared to a general-purpose warehouse.

The energy recovery mechanisms are then integrated into the water supply system of the sprinkler system. This can involve installing energy recovery turbines in the return water pipelines. These turbines can capture the energy from the water flow during the operation of the sprinkler system and convert it into electrical energy, which can be reused for other low power operations in the warehouse, such as lighting or ventilation fans.

For validation, a series of fire simulation tests were carried out. These tests simulate different fire scenarios, including the location, scale, and combustion rate of the fire. The performance of the ESFR sprinklers in terms of fire suppression speed, water coverage area, and energy recovery efficiency was measured. For instance, the time it takes for the sprinklers to control the fire and the amount of energy recovered during the firefighting process are recorded. Based on the test results, further optimization can be made to the design of the warehouse protection system. This approach ensures that the upgraded warehouse protection system not only effectively suppresses fires but also achieves energy saving goals, which is in line with the requirements of modern sustainable industrial building design [11].

5.2. Civil building demonstrations

5.2.1. High-rise residential water conservation

In LEED certified high rise residential towers, implementing pressure regulated sprinklers integrated with greywater systems for water conservation in building fire protection systems is a practical approach. Pressure regulated sprinklers are designed to maintain a consistent water flow rate regardless of the supply pressure variations. This feature not only ensures effective fire suppression but also helps in conserving water by preventing over spraying.

When integrating with greywater systems, greywater, which is the relatively clean wastewater from sources like sinks, showers, and washing machines, can be treated and reused in the sprinkler system. This significantly reduces the reliance on fresh water resources.

For practical implementation, a comprehensive design plan is required. The greywater treatment plant needs to be carefully located within the building to ensure smooth operation and easy maintenance. Piping systems for both greywater supply and sprinkler distribution should be well designed to avoid cross contamination and ensure proper water flow.

Validation of this approach is crucial. It can be achieved through a series of tests. Flow rate and pressure tests are carried out to ensure that the pressure regulated sprinklers function as expected. Microbiological and chemical tests are conducted on the treated greywater to verify its compliance with the standards for use in fire protection systems. Additionally, long term monitoring of water consumption and firefighting effectiveness can provide valuable data for further optimization [12]. This combination of practical implementation and validation in high rise residential buildings can lead to more sustainable and efficient automatic sprinkler fire extinguishing systems.

5.2.2. Mixed-use complex system integration

In the practical implementation and validation of mixed-use complex system integration for civil building demonstrations in the context of coordinating sprinkler networks with HVAC and lighting systems for holistic energy management, several key aspects need to be addressed. First, during the implementation phase, detailed design blueprints of the sprinkler, HVAC, and lighting systems should be carefully reviewed and integrated. For example, the layout of sprinkler pipes should be planned in a way that it does not interfere with the ductwork of the HVAC system, while also considering the positioning of lighting fixtures to ensure unobstructed water spray in case of a fire [13].

Sensors play a crucial role in this integration. Smoke and heat sensors in the sprinkler system can be linked to the HVAC system to adjust air circulation in case of a fire, preventing the spread of smoke. At the same time, the lighting system can be programmed to switch to emergency lighting mode when the sprinkler system is activated.

Validation is then carried out through a series of tests. Simulated fire scenarios are created in a test area of the mixed-use complex. The performance of the integrated system is monitored, including the activation time of the sprinkler system, the response of the HVAC system in terms of air control, and the speed at which the lighting system switches to emergency mode. Any discrepancies found during the tests are analyzed, and corresponding adjustments are made to the system design. This iterative process of implementation and validation helps to ensure the efficient and reliable operation of the integrated system in real world civil building applications.

5.3. Performance benchmark analysis

5.3.1. Water-energy nexus metrics

In the practical implementation and validation of the design and optimization strategy for automatic sprinkler fire extinguishing in building fire protection systems, the water energy nexus metrics play a crucial role. These metrics are designed to evaluate the tradeoffs and synergies between water consumption and energy use in the system.

For traditional automatic sprinkler systems, a certain amount of water was required to be discharged at a specific pressure to effectively suppress fires. The energy is mainly consumed in pumping water to reach the required pressure for sprinkler operation. When optimizing the system, new materials, more efficient pump designs, or intelligent control strategies might be introduced. For example, using variable speed pumps can adjust the energy input according to the actual water demand during a fire event, potentially reducing overall energy consumption while maintaining effective water discharge [14].

To measure the water energy nexus, metrics such as water energy ratio (the amount of water used per unit of energy consumed) can be calculated. A higher water energy ratio indicates a more efficient use of resources, meaning that more water can be delivered to suppress the fire with less energy input. Additionally, metrics like total water consumption during a fire scenario and the corresponding energy input for different system configurations (traditional and optimized) can be compared. These benchmark analyses based on water energy nexus metrics help in validating whether the optimization strategies not only improve firefighting effectiveness but also enhance the resource use efficiency in the automatic sprinkler fire extinguishing systems.

5.3.2. Lifecycle cost-benefit projections

For the performance benchmark analysis of the automatic sprinkler fire extinguishing system in building fire protection, a series of metrics need to be established. These may include response time, water distribution uniformity, and fire suppression effectiveness. Response time is crucial as it determines how quickly the system can start working once a fire is detected. A shorter response time can significantly reduce the spread of the fire. Water distribution uniformity ensures that the entire fire prone area is adequately covered with water, maximizing the fire extinguishing effect. Fire suppression effectiveness can be measured by the ability to control and extinguish fires of different scales and types.

When making lifecycle cost benefit projections for different design scenarios of the automatic sprinkler system, consider all costs and benefits over a 20 years period. Costs include initial installation costs, which cover equipment purchase, piping installation, and system commissioning. Maintenance costs are also significant, involving regular inspections, component replacements, and system upgrades. Energy costs for operating the system, such as pump power consumption, should not be overlooked. On the benefit side, the most obvious is the potential reduction in property damage and loss of life due to effective fire suppression. Additionally, in some regions, buildings with compliant automatic sprinkler systems may receive insurance premium discounts, which is also a long-term benefit. By comprehensively evaluating these costs and benefits, a more accurate projection of the lifecycle cost benefit of different design scenarios can be obtained, providing a solid basis for decision making in system design and optimization.

6. Conclusion

In conclusion, the design and optimization strategy of automatic sprinkler fire extinguishing in building fire protection systems is a complex yet crucial topic. The synthesized findings highlight the significance of achieving a balanced optimization between ensuring fire safety and sustainable resource utilization. This balance was not only essential for immediate fire protection but also for the long term environmental and economic viability of buildings.

The proposed adaptive design frameworks tailored to various building typologies offer a practical approach. Different building types, such as residential, commercial, and industrial, have unique fire risks and usage patterns. By adapting the design of automatic sprinkler systems accordingly, we can enhance their effectiveness.

Looking ahead, future research directions in AI driven predictive system tuning hold great promise. AI can analyze a vast amount of data, including historical fire incidents, building occupancy, and environmental factors, to predict fire risks more accurately. This enables pre-emptive activation of sprinkler systems and better resource allocation. Additionally, the application of nanomaterials in sprinkler systems could potentially revolutionize their performance. Nanomaterials may offer enhanced heat dissipation properties, corrosion resistance, and more efficient water distribution, further improving the overall fire extinguishing capabilities. Overall, continuous research and innovation in these areas will contribute to the development of more advanced and effective automatic sprinkler fire extinguishing systems in building fire protection.

Disclosure statement

The author declares no conflict of interest.

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Research on Key Technologies and Quality Control of Installation and Construction of Building HVAC Equipment

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Abstract: Building HVAC equipment installation is vital for indoor comfort, energy efficiency, and environmental quality. Key technologies like vibration control, pipe network alignment, and thermal stress compensation, along with a multi-faceted quality standards framework, are crucial. Effective process management, practical application analysis, and the integration of robotics, IoT, and AI enhance quality and efficiency. Sustainable development strategies and lifecycle-oriented quality management are also essential for future progress.

Keywords: HVAC equipment installation; Key technologies; Quality control

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1. Introduction

In the realm of building construction, the installation and construction of HVAC equipment hold great importance. With the construction industry's continuous evolution and the escalating demand for high quality indoor environments, the study of key technologies and quality control in this area has become a crucial academic pursuit. For instance, vibration control, as one of the critical technologies in HVAC equipment installation, has been systematically reviewed in recent research, highlighting its significance in ensuring operational stability and reducing noise [1]. In line with the global trend towards sustainable development, policies such as the "Sustainable Energy for All" initiative launched in 2012 encourage the integration of energy efficient and environmentally friendly practices in building systems, including HVAC. This paper delves into the key technologies, quality control, and practical applications in HVAC equipment installation, exploring how to enhance installation levels while adhering to sustainable development principles, aiming to provide theoretical and practical guidance for the industry.

2. Core technologies for HVAC equipment installation

2.1. Installation process design

For the installation process design of building HVAC equipment, under complex building structures, it is essential to consider the systematic installation flow design principles. First, the layout of the equipment needs to be carefully planned. This requires taking into account factors such as the building's architectural features, space utilization, and the intended functionality of the HVAC system. For example, the location of air handling units should be determined based on the distribution of air supply and return ducts to ensure efficient air circulation [2].

Workflow optimization strategies also play a crucial role. One aspect is to streamline the sequence of installation tasks. For large scale HVAC equipment, tasks like equipment transportation, assembly, and pipeline connection need to be arranged in a logical order to minimize delays and rework. For instance, pre assembly of components off-site can be carried out to reduce on-site installation time. Additionally, modern project management tools and techniques can be applied to monitor and control the installation process. This includes using scheduling software to set milestones and allocate resources effectively, ensuring that the entire installation project progresses smoothly and is completed within the specified time and budget constraints. By adhering to these systematic installation flow design principles and implementing workflow optimization strategies, the installation of building HVAC equipment can be carried out more efficiently and with higher quality.

2.2. Key technical challenges

One of the key technical challenges in HVAC equipment installation lies in vibration control during mechanical installation. The operation of HVAC mechanical components can generate significant vibrations, which not only cause noise pollution, affecting the comfort of the building occupants, but also potentially lead to damage to the equipment itself over time due to fatigue stress [3]. Precise installation techniques and the use of appropriate vibration isolation materials are crucial to mitigate these vibrations.

Another challenge is the pipe network alignment precision. In an HVAC system, a complex network of pipes is used to transport air, water, or refrigerants. Any misalignment in the pipes can disrupt the fluid flow, leading to inefficiencies in the system. This requires highly accurate measurement tools and skilled installers to ensure that the pipes are aligned correctly, both horizontally and vertically, to maintain the smooth operation of the system.

Thermal stress compensation in HVAC system connections is also a significant challenge. As the HVAC system operates, temperature changes can cause expansion and contraction of the pipes and equipment. If not properly compensated for, these thermal stresses can cause leaks in the connections, or even structural damage to the pipes. Designing effective thermal expansion joints and using materials with appropriate thermal expansion coefficients are necessary to address this challenge.

3. Quality control system construction

3.1. Quality standards framework

The quality standards framework for the installation and construction of building HVAC equipment is multi-faceted. It integrates ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) standards, which are widely recognized in the field of HVAC. ASHRAE standards cover various aspects such as energy efficiency, indoor air quality, and system performance [4]. These standards ensure that the HVAC systems are designed and installed to meet a certain level of technical performance, for example, setting limits on the energy consumption of different types of HVAC equipment.

LEED (Leadership in Energy and Environmental Design) certification requirements are also incorporated. LEED focuses on the overall environmental impact of the building, including the role of the HVAC system. It promotes sustainable design and operation of HVAC systems, such as encouraging the use of renewable energy sources in HVAC operations, improving the energy recovery efficiency of the system, and reducing greenhouse gas emissions.

Regional construction codes play a crucial part as well. These codes are tailored to the local climate, building types, and safety requirements. For instance, in areas with extreme climates, the codes may require higher insulation levels for HVAC ducts to minimize heat loss or gain. They also ensure that the installation and construction of HVAC equipment meet local safety regulations, like proper grounding of electrical components in the HVAC system. By integrating these three elements ASHRAE standards, LEED certification requirements, and regional construction codes a comprehensive quality standards framework is established for the installation and construction of building HVAC equipment.

3.2. Process management measures

To ensure the quality of building HVAC equipment installation and construction, effective process management measures are crucial. Firstly, a detailed construction plan should be formulated. This plan should cover every step of the installation process, from equipment delivery and inspection to actual installation and commissioning. By doing so, potential issues can be anticipated in advance, and corresponding countermeasures can be prepared.

Secondly, strict control over construction operations is essential. Workers need to follow standardized operating procedures. For example, when installing pipes, attention should be paid to the slope, connection tightness, and insulation measures to prevent problems such as water leakage and heat loss. Supervisors should regularly inspect the construction site to ensure that all operations comply with the requirements.

In addition, real time monitoring solutions for critical installation nodes should be implemented, as developed in the BIM based collaborative management mechanisms [5]. This enables timely detection of any deviations from the standard during the installation process. Through real time data collection and analysis, immediate adjustments can be made, thus reducing the risk of quality problems. Regular communication among different teams involved in the project, including designers, installers, and supervisors, is also necessary. This can help resolve potential conflicts promptly and ensure the smooth progress of the installation work. Overall, these process management measures contribute to the high-quality installation and construction of building HVAC equipment.

4. Practical application analysis

4.1. Case study methodology

4.1.1. Project background selection

In the research on the key technologies and quality control of the installation and construction of building HVAC equipment, representative commercial complex projects are chosen as the research objects. Commercial complexes typically feature large scale areas, high density occupancies, and diverse functional zones, such as shopping areas, dining areas, and entertainment areas. These characteristics demand a high performance and well configured HVAC system to ensure comfortable indoor environmental conditions.

The diversified HVAC system configurations in these commercial complex projects play a crucial role. For example, variable refrigerant flow (VRF) systems may be employed in some areas for their flexibility in temperature control and energy saving features. Central air conditioning systems, on the other hand, could be utilized in large scale open plan areas to provide uniform cooling or heating. The presence of such diverse configurations allows for a comprehensive study of different key installation technologies, such as refrigerant pipe installation in VRF systems and ductwork installation in central air conditioning systems.

Moreover, by focusing on commercial complex projects, the study can better address the real-world challenges in quality control during HVAC equipment installation and construction. These challenges include coordinating with other building systems, meeting strict indoor air quality requirements, and ensuring long - term reliable operation. Such research based on commercial complex projects can offer practical and valuable insights, which are of great significance for promoting the overall quality of building HVAC equipment installation and construction [6].

4.1.2. Technical implementation evaluation

In the Technical Implementation Evaluation within the Practical Application Analysis through Case Study Methodology, a comparative analysis of equipment installation efficiency and system performance metrics before and after the technology application is of great significance. This evaluation aims to precisely measure the real-world impact of the key technologies in the installation and construction of building HVAC equipment.

Regarding equipment installation efficiency, factors such as the time taken for component assembly, the number of workers involved, and the frequency of installation related issues are carefully examined. By comparing the pre technology application situation with the post implementation scenario, it becomes possible to determine whether the new technologies have led to a reduction in installation time, an optimization of labor resources, or a decrease in installation related setbacks. For instance, advanced prefabrication techniques might have enabled quicker on-site assembly, thus enhancing the overall installation efficiency [7].

System performance metrics, on the other hand, cover aspects like energy consumption, indoor air quality, and temperature and humidity control accuracy. A lower energy consumption rate after the technology implementation indicates improved energy saving performance. Enhanced indoor air quality could imply that the new technologies have optimized air filtration and ventilation mechanisms. Precise temperature and humidity control showcases the effectiveness of control algorithms and sensor technologies. Through this comprehensive evaluation of equipment installation efficiency and system performance metrics, a clear understanding of the practical effectiveness of the key technologies in the installation and construction of building HVAC equipment can be obtained, providing valuable insights for future improvements and applications.

4.2. Quality performance verification

4.2.1. System stability testing

Under full load conditions, the system stability testing of building HVAC equipment installation and construction focuses on operational vibration analysis and thermal cycle testing. Operational vibration analysis is crucial as excessive vibration not only affects the comfort of the building occupants but also poses a threat to the long-term operation of the equipment. By measuring and analyzing vibration parameters such as amplitude, frequency, and direction during the full load operation of the HVAC equipment, potential problems like unbalanced rotors, loose components, or improper installation can be detected [8]. For instance, if the vibration amplitude exceeds the standard value, it might indicate that the fan blades are not properly balanced, which could lead to accelerated wear and tear of bearings and ultimately equipment failure.

Thermal cycle testing, on the other hand, simulates the actual working environment of the HVAC system where temperature changes occur cyclically. This helps to assess the adaptability of the equipment to different temperature conditions. During the test, the system is subjected to a series of temperature rises and drops. The equipment's performance, including its cooling or heating capacity, energy consumption, and the stability of key components, is closely monitored. If the equipment fails to maintain stable performance during thermal cycling, it may suggest issues with the thermal management system, such as ineffective insulation or improper refrigerant flow control. Overall, these two aspects of system stability testing are essential for ensuring the reliable and long-term operation of building HVAC equipment.

4.2.2. Energy efficiency validation

In the Energy Efficiency Validation within the Practical Application Analysis of Quality Performance Verification, EnergyPlus software is employed to conduct a comprehensive energy consumption simulation. This simulation meticulously models the energy usage patterns of the building HVAC equipment under various scenarios, taking into account factors such as building orientation, insulation properties, occupancy schedules, and equipment operation characteristics. By accurately simulating the energy consumption, it provides a theoretical baseline for evaluating the energy efficiency of the HVAC system.

Subsequently, field measurement data are collected. These data are obtained from actual operating conditions of the installed HVAC equipment in the building. The measured parameters may include power consumption of different components, indoor and outdoor temperature differentials, air flow rates, and energy consumption of the entire system over a specific period.

The energy consumption simulation results and the field measurement data are then compared. This comparison serves as a crucial means to validate the energy efficiency of the building HVAC equipment installation and construction. Any significant discrepancies between the simulation and measurement may indicate issues in the design, installation, or operation of the equipment. For instance, if the measured energy consumption is much higher than the simulated value, it could imply problems such as improper equipment sizing, inefficient installation leading to energy losses, or suboptimal control strategies. Through this in - depth comparison and analysis, the energy efficiency of the building HVAC equipment can be effectively verified, providing valuable insights for further improvement and quality control in the installation and construction process [9].

5. Technical optimization suggestions

5.1. Intelligent installation innovation

5.1.1. Robotics integration

The integration of robotics in the installation and construction of building HVAC equipment represents a significant step forward in intelligent installation innovation. By leveraging SLAM navigation technology, automated alignment solutions for heavy equipment installation can be achieved.

Robots equipped with advanced sensors can precisely map the installation environment, creating a real-time three-dimensional model. This model allows the robots to plan optimal paths for equipment transportation and installation, avoiding obstacles and ensuring accurate alignment. For example, in a large-scale commercial building's HVAC system installation, robots can navigate through complex spaces such as basements and mechanical rooms.

These robots are designed to handle the heavy lifting tasks associated with HVAC equipment. They can lift, position, and align components with a high degree of precision, reducing human error. In terms of quality control, the robotic systems can continuously monitor the installation process, collecting data on parameters such as alignment accuracy, connection tightness, etc. Any deviations from the set standards can be immediately detected and corrected.

Furthermore, the use of robotics in this field also improves work efficiency. Multiple robots can work simultaneously, coordinated by a central control system, to complete different stages of the installation process in parallel. In conclusion, the integration of robotics, especially when combined with SLAM navigation technology, offers a promising solution for the key technologies and quality control in the installation and construction of building HVAC equipment [10].

5.1.2. IoT-enabled monitoring

In the context of the installation and construction of building HVAC equipment, an IoT-enabled monitoring system with a proposed wireless sensor network architecture plays a crucial role. This architecture is designed to achieve real - time stress/strain monitoring during the installation phases [11]. By leveraging IoT technology, a network of wireless sensors can be strategically placed on the HVAC equipment and relevant installation structures. These sensors are capable of accurately detecting and transmitting data regarding stress and strain in real time. This real time data collection enables installation teams to closely monitor the physical conditions of the equipment during installation. For example, sudden changes in stress or strain values can indicate potential problems such as improper installation, unbalanced loads, or structural defects. The data transmitted by the sensors can be received and analyzed through a central monitoring platform. The platform uses advanced algorithms to process the data, providing intuitive visualizations and alerts. This allows installers to make timely adjustments and corrections, ensuring the installation process proceeds smoothly and the long-term stability and safety of the HVAC equipment. The IoT enabled monitoring not only improves the quality control during the installation but also contributes to reducing the risk of future malfunctions and maintenance costs associated with the building's HVAC system.

5.2. Quality assurance enhancement

5.2.1. Digital twin applications

Developing physics based digital twin models is a crucial step in achieving predictive quality control in HVAC component assembly. These digital twin models are constructed based on the physical principles governing the operation of HVAC components. For instance, they incorporate factors such as heat transfer, fluid dynamics, and thermodynamics relevant to the specific component being modeled [12].

By creating these models, it becomes possible to simulate the assembly process in a virtual environment. This simulation can predict potential quality issues before they occur in the actual physical assembly. For example, the model can detect if there will be misalignments in pipes during the connection process, or if certain parts might experience excessive stress due to improper installation sequences.

Furthermore, the digital twin models can be updated in real time with data from sensors placed on the actual components during the assembly process. This real time data enables the model to adapt and provide more accurate predictions, continuously enhancing the quality control process. The digital twin also serves as a valuable tool for training personnel. Trainees can practice the assembly process using the digital twin, familiarizing themselves with the correct procedures and potential problem-solving methods, thus reducing the likelihood of quality - related mistakes during actual on-site assembly. Overall, the physics based digital twin models play a vital role in ensuring high quality HVAC component assembly.

5.2.2. AI-driven defect detection

AI driven Defect Detection can be realized by implementing deep learning algorithms. Point cloud data analysis serves as a crucial tool in this process. Point cloud data, which can comprehensively represent the geometric information of the HVAC equipment and its installation environment, is collected from the installation site. Deep learning-based algorithms are then applied to analyze this data [13]. These algorithms are trained to recognize patterns that indicate installation deviations. For example, convolutional neural networks (CNNs) can be used to process the point cloud data. CNNs are good at extracting local features from data. They can identify whether the position of the equipment is off set, if the angles of components are incorrect, or if there are any missing parts in the installation. Through continuous training with a large number of labeled point cloud data samples, the algorithm can improve its accuracy in identifying installation defects. Once the algorithm is well trained, it can automatically detect potential defects during the installation and construction process of building HVAC equipment in real time. This not only improves the efficiency of defect detection but also enhances the accuracy, reducing the reliance on manual inspection and minimizing human error related omissions in defect identification.

5.3. Sustainable development strategies

5.3.1. Low-carbon installation techniques

Researches prefabricated modular installation methods to minimize construction waste generation. This approach is of great significance for achieving low carbon installation in the building HVAC equipment installation and construction. By adopting prefabricated modular installation, a large part of the manufacturing process can be carried out in a factory environment. This not only improves production efficiency but also reduces on-site cutting, welding and other operations, thereby significantly reducing the generation of construction waste such as scraps and dust [14].

In the factory, with advanced production equipment and standardized production processes, the accuracy and quality of modular components can be better guaranteed. These prefabricated modules can be directly transported to the construction site for assembly, which simplifies the on-site installation process. Workers only need to connect the modules according to the design requirements, reducing the complexity and time consumption of on-site construction.

Moreover, the prefabricated modular installation method is conducive to the reuse and recycling of materials. When the HVAC equipment needs to be updated or maintained in the future, the modular components can be easily disassembled. Some components in good condition can be reused, and the waste components can also be recycled more conveniently according to their material properties, further promoting the sustainable development of the construction industry.

5.3.2. Lifecycle-oriented quality management

When it comes to the installation and construction of building HVAC equipment, establishing maintenance focused quality tracking mechanisms considering equipment service lifecycle characteristics is crucial.

Throughout the equipment's lifecycle, from the initial installation phase to its long-term operation and eventual decommissioning, quality management should be an ever-present concern. During installation, strict quality control measures need to be implemented. This includes ensuring that components are correctly installed, connections are secure, and the overall system is configured to meet design specifications. Meticulous inspection at this stage can prevent potential problems from emerging during operation.

As the equipment enters the operation phase, continuous quality tracking is essential. Regular monitoring of key performance indicators such as energy consumption, temperature regulation accuracy, and air quality can help detect early signs of degradation or malfunction. Based on the data collected, predictive maintenance strategies can be formulated. For example, if the energy consumption of an air conditioning unit starts to increase steadily without a corresponding change in usage patterns, it could indicate a problem with the compressor or refrigerant system, prompting timely maintenance.

Finally, at the end-of-life stage, proper disposal and recycling of HVAC equipment should be part of the quality management process. This not only ensures environmental sustainability but also reflects the overall quality commitment to the entire lifecycle of the equipment. By comprehensively managing quality throughout the equipment's lifecycle, the long-term performance, reliability, and sustainability of building HVAC systems can be significantly enhanced.

6. Conclusion

In conclusion, the installation and construction of building HVAC equipment are of great significance in the construction industry. The key technologies, such as precise equipment positioning, efficient pipeline connection, and intelligent control system integration, have witnessed remarkable technological breakthroughs. These advancements not only improve the installation efficiency but also enhance the overall performance of HVAC systems.

Regarding quality control, proactive methodologies, including strict pre-installation inspections, in process quality monitoring, and comprehensive post-installation testing, have been proven effective in ensuring the reliability and durability of HVAC installations.

Looking ahead, the future of HVAC installation technologies lies in the integration of sustainability and digital transformation. Incorporating renewable energy sources into HVAC systems, such as solar powered air conditioning units, can significantly reduce the environmental impact. Digital transformation, on the other hand, enables real time monitoring, predictive maintenance, and intelligent optimization of HVAC operations. This will lead to more energy efficient, cost effective, and user-friendly building environments. Overall, continuous innovation in key technologies and strict quality control will be the cornerstones for the sustainable development of building HVAC equipment installation and construction.

Disclosure statement

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Practical Research on the Effective Management of Change Visas and Dynamic Cost Control in the Construction Stage of Construction Projects

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Abstract: Construction project construction stage requires effective change visa management and dynamic cost control. This paper defines both, presents related theories, and details challenges in traditional methods. It then proposes an integrated model with system architecture, functional modules, and practical strategies like BIM integrated workflows. A case study validates the effectiveness, and future research on AI enhanced change prediction and blockchain based audit trails is suggested.

Keywords: Change visas; Dynamic cost control; Construction projects

Online publication: Dec 15, 2025

1. Introduction

In the construction industry, the effective management of change visas and dynamic cost control during the construction stage of projects is of great significance. The "Construction Project Cost Management Regulations" emphasizes the importance of scientific cost management and strict control of project changes. Change visas, which are affected by various factors, can impact project cost, schedule, and quality. Dynamic cost control is essential to ensure projects stay within budget. Traditional methods have limitations, while integrated models, BIM-integrated workflows, such as the BIM-based information management system applied in construction and demolition waste management for greenhouse gas quantification and mitigation and predictive analytics offer solutions [1]. Standardized protocols, cross-departmental collaboration, and modern systems are also crucial. Research on these aspects, as guided by the policy, can help construction project managers improve performance and ensure project success.

2. Theoretical framework and core concepts

2.1. Definition of change visas and dynamic cost control

Change visas, also known as variation orders, in the construction stage of construction projects refer to formal instructions issued by the employer or the engineer to make changes to the original contract scope, quantity, quality, or construction sequence of the project [2]. These changes can be initiated due to various reasons such as design modifications, unforeseen site conditions, or client requested adjustments. Change visas have a direct impact on the project cost, time, and quality. They are crucial documents that need to be carefully managed as they can significantly alter the initial project plan and budget.

Dynamic cost control, on the other hand, is a continuous process of monitoring, analyzing, and adjusting the project cost throughout the construction stage. It involves comparing the actual cost incurred with the planned cost, identifying any variances, and taking appropriate corrective actions. Dynamic cost control is not a static process but rather an iterative one that adapts to the dynamic nature of construction projects. It considers factors like changes in market prices of materials, labor productivity fluctuations, and the impact of change visas. By implementing effective dynamic cost control, project managers can ensure that the project stays within the budget, minimize cost overruns, and achieve the desired economic benefits. Overall, understanding the definitions of change visas and dynamic cost control is fundamental for effective management in the construction stage of construction projects.

2.2. Theoretical basis for cost management

Cost management in construction projects is founded on several key theoretical concepts. Lifecycle cost theory plays a vital role. This theory emphasizes considering all costs associated with a construction project throughout its entire lifecycle, from the initial planning and design phase, through construction, to operation, maintenance, and even demolition [3]. By taking a holistic view of costs, it enables project managers to make more informed decisions. For instance, a more expensive but durable building material might seem costly upfront, but over the long term, it could result in lower maintenance and replacement costs, thus reducing the overall lifecycle cost.

Change management theory is also crucial. In construction projects, changes are inevitable due to various factors like design modifications, unforeseen site conditions, or client requests. This theory provides a structured approach to handle these changes effectively. It involves processes such as change identification, impact assessment, approval, and implementation. Proper change management can prevent cost overruns caused by ad hoc changes, ensuring that any adjustments to the project scope are accompanied by a corresponding evaluation of cost implications.

Real time cost control principles are the third cornerstone. In the fast paced environment of construction, real time monitoring and control of costs are essential. This requires the use of modern technologies and tools to collect, analyze, and report cost data promptly. By having up to date cost information, project managers can quickly identify variances from the budget, take corrective actions, and keep the project's cost performance on track.

3. Current challenges in change visa management and cost control

3.1. Issues in change visa execution

During the execution of change visas in the construction stage of construction projects, several significant challenges emerge. Inefficiencies in approval workflows stand out as a major hurdle. Lengthy and convoluted approval processes can cause substantial delays. For instance, multiple levels of review and sign off, sometimes involving various departments with different priorities and schedules, may lead to bottlenecks. This not only slows down the implementation of change visas but also impacts the overall project timeline, potentially increasing costs due to extended labor and equipment rental periods [4].

Documentation inconsistencies are another crucial issue. Inaccurate, incomplete, or conflicting documentation can create misunderstandings among stakeholders. For example, discrepancies between the description of the change in the visa and the actual work carried out, or between different versions of the same document, can lead to disputes over scope, cost, and quality. These disputes often require additional time and resources to resolve, disrupting the project's progress.

Stakeholder coordination challenges also pose difficulties. Construction projects involve a diverse range of stakeholders, including contractors, subcontractors, designers, and clients. Each stakeholder may have different interests and expectations regarding change visas. For example, contractors may be more concerned with cost effectiveness and timely execution, while clients may focus on achieving the desired functionality. Coordinating these different perspectives and ensuring effective communication is essential. However, misaligned goals, lack of clear communication channels, or poor information sharing can result in inefficiencies and conflicts during the change visa execution process.

3.2. Limitations of traditional cost control methods

Traditional cost control methods in construction projects often face several limitations. One of the major drawbacks is the static budget constraints. These methods typically rely on a fixed budget set at the beginning of the project, assuming that project conditions will remain relatively stable. However, in reality, construction projects are highly dynamic, with numerous factors such as design changes, unforeseen site conditions, and market fluctuations that can impact costs. This static budget fails to adapt to these changes, leading to cost overruns [5].

Another limitation is the delayed cost feedback. Traditional methods usually depend on periodic reports, which means that cost information is not available in real time. By the time the cost deviations are identified, significant cost overruns may have already occurred, leaving little room for effective corrective actions.

Furthermore, traditional cost control methods often lack an adequate response mechanism to dynamic project changes. They are not well equipped to handle the complex and rapid changes that occur during the construction stage, such as change visas. When a change occurs, the existing cost control framework may not be able to accurately assess the impact on costs, allocate resources appropriately, or adjust the cost control strategies promptly. As a result, the project may experience disruptions in cost management, ultimately affecting the overall project performance.

4. Integrated model for dynamic cost control with change visa management

4.1. Framework design of the model

4.1.1. System architecture

The system architecture of the integrated model for dynamic cost control with change visa management aims to seamlessly integrate change visa workflows, real time cost monitoring, and predictive analytics in a closed loop framework.

The change visa workflow component serves as the starting point. It details the entire process from the initiation of a change request due to various project related factors such as design adjustments or unforeseen site conditions. This process involves multiple stakeholders, including contractors, designers, and project managers. Each step of the workflow, from submission, review, approval to implementation, is clearly defined to ensure transparency and accountability [6].

Real time cost monitoring is closely intertwined with the change visa workflow. As the change visa progresses, cost related data is continuously collected. This includes material costs, labor costs, and any additional expenses associated with the change. Advanced cost monitoring tools are employed to track these costs accurately, enabling project teams to have an up to date understanding of the financial implications of each change visa.

Predictive analytics, on the other hand, uses historical data from past change visas and current project data. By applying statistical models and machine learning algorithms, it forecasts potential cost overruns, schedule delays, and other risks associated with the change visas. This proactive approach allows project managers to take preventive measures in a timely manner.

These three components form a closed loop system. The results of predictive analytics can influence the change visa workflow, for example, by suggesting alternative change solutions to avoid excessive costs. Real time cost monitoring feeds back into both the change visa workflow and predictive analytics, providing fresh data for better decision making.

4.1.2. Functional modules

The functional modules of the model include detailed modules for change impact assessment, cost database updating, and risk alert mechanisms. The change impact assessment module is designed to accurately evaluate the influence of change visas on project costs. It analyzes various factors such as changes in work scope, schedule adjustments, and material substitutions caused by change visas, and quantifies their impacts on cost through specific algorithms and data analysis methods [7]. This enables project managers to understand the cost implications of each change visa clearly.

The cost database updating module is crucial for maintaining the accuracy of cost information. As change visas occur, relevant cost data, including new material prices, labor costs for additional work, and equipment rental fees, need to be promptly updated in the cost database. This ensures that the cost data used for cost control and decision making is up to date and reflects the real time situation of the project.

The risk alert mechanism module monitors the cost related risks associated with change visas. By setting up risk thresholds and using risk assessment models, it can timely detect potential cost - overruns or abnormal cost fluctuations caused by change visas. Once a risk is identified, it sends alerts to relevant personnel, enabling them to take preventive measures in a timely manner, such as adjusting the project plan, negotiating with contractors, or re-evaluating the feasibility of change visas. These three functional modules work together to support effective dynamic cost control in construction projects with change visa management.

4.2. Data-driven decision support

4.2.1. BIM-based cost tracking

Developing BIM integrated workflows is crucial for effective cost tracking in the context of change visa management and dynamic cost control. These workflows enable the visualization of change impacts. By integrating Building Information Modeling (BIM) technology, project teams can vividly see how a change visa affects the overall project structure, layout, and components. For example, a design change in a building's façade can be visualized in the BIM model, showing its impact on materials, labor, and time.

Moreover, BIM integrated workflows automate quantity takeoffs. This automation significantly reduces human errors associated with manual quantity calculations. It quickly and accurately determines the quantities of materials such as concrete, steel, and bricks required for a modified part of the project due to a change visa. The accurate quantity data, in turn, is essential for precise cost estimation.

These automated quantity takeoffs and visualizations form the basis of BIM based cost tracking. Cost managers can rely on the data provided by BIM integrated workflows to monitor costs in real time. As changes occur, the BIM model is updated, and the associated cost implications are immediately reflected, allowing for timely decision making. With this approach, cost control becomes more proactive rather than reactive, enabling project teams to stay within budget constraints throughout the construction stage of construction projects [8].

4.2.2. Predictive analytics for cost deviation

Predictive analytics for cost deviation is a crucial component in the integrated model for dynamic cost control with change visa management. Machine learning algorithms are implemented to forecast cost variations resulting from change visas. These algorithms can analyze historical data related to change visas, such as the type of change, the project phase when the change occurred, the involved parties, and the resulting cost impacts. By processing this large volume of data, machine learning models can identify patterns and relationships that are difficult for humans to detect [9]. For example, they may find that certain types of change visas in specific project stages are more likely to lead to significant cost increases. Once these patterns are recognized, the model can predict future cost deviations when new change visas are issued. This enables project managers to anticipate potential cost overruns in advance. They can then take proactive measures, such as re - evaluating the project budget, adjusting resource allocation, or negotiating more favorable terms with contractors. Predictive analytics not only helps in cost control but also improves overall project management efficiency by providing data driven insights for decision - making in the face of change visas.

5. Implementation strategies and case validation

5.1. Process optimization measures

5.1.1. Standardized change authorization protocol

For the standardized change authorization protocol, design streamlined approval hierarchies and digital signature mechanisms for change visas. Simplifying the approval hierarchies is crucial as in traditional construction project change management, complex and multi-level approval processes often lead to inefficiencies, delays, and increased costs. By streamlining these hierarchies, the time from the initiation of a change request to its approval can be significantly reduced. For example, identifying key decision makers at each relevant stage and directly routing the change visa through them can eliminate redundant approval steps.

Digital signature mechanisms play an important role in enhancing the efficiency and security of the change authorization process. Digital signatures ensure the authenticity and integrity of the change visa documents. They enable remote approval, breaking the geographical constraints that may slow down the traditional paper based signature process. This means that stakeholders can review and sign change visas promptly regardless of their location. Moreover, digital signatures are legally recognized in many regions, providing a reliable way to approve change visas. These two aspects, streamlined approval hierarchies and digital signature mechanisms, work in tandem to standardize the change authorization protocol, thus contributing to the effective management of change visas and dynamic cost control in construction projects [10].

5.1.2. Cross-departmental collaboration mechanisms

To enhance cross departmental collaboration mechanisms for effective management of change visas and dynamic cost control in construction projects' construction stage, integrated communication platforms linking design, procurement, and cost teams are essential. These platforms break down the silos between departments. Design teams can promptly share any modifications in the design, which might trigger change visas. For instance, if there is a design alteration to improve the functionality of a building's layout, this information can be instantly conveyed to the procurement team. The procurement team, in turn, can then assess the impact on material costs and availability. They can inform the cost team about potential price fluctuations due to changes in material requirements. The cost team can use this information to accurately update the cost estimates and adjust the dynamic cost control strategies.

In a real world case, a large scale commercial construction project implemented such an integrated communication platform [11]. Initially, without the platform, design changes were often communicated tardily, leading to delays in procurement and unexpected cost overruns. After establishing the platform, all departments were on the same page. When the design team proposed a change to use more energy efficient materials, the procurement team quickly sourced suppliers and provided cost quotes to the cost team. The cost team was able to incorporate these changes into the cost plan in a timely manner, effectively controlling the project cost and minimizing the number of unforeseen change visas.

5.2. Technological enablers

5.2.1. Cloud-based cost management systems

Cloud Based Cost Management Systems play a crucial role in the effective management of change visas and dynamic cost control in the construction stage of construction projects. By deploying centralized databases, these systems enable real time cost data sharing. This means that all relevant parties, including project managers, contractors, and cost estimators, can access the most up to date cost information. For example, when a change visa occurs, the cost impact can be immediately recorded and shared across the team, ensuring that everyone is on the same page regarding the financial implications [12].

Version control is another key feature. It helps to track the evolution of cost data over time. In a construction project, cost estimates may change multiple times due to various factors such as design modifications or market price fluctuations. With version control in cloud - based systems, each change can be documented, allowing for easy review and analysis. This not only provides transparency but also helps in auditing processes. For instance, if there is a dispute regarding a cost item, the historical versions of the cost data can be retrieved to understand how the figure was derived. Overall, cloud based cost management systems enhance the efficiency and accuracy of cost control, facilitating better decision - making during the construction stage.

5.2.2. Mobile reporting tools

Developing field data collection apps for instant change documentation and cost impact calculation is a crucial aspect of mobile reporting tools in the effective management of change visas and dynamic cost control during the construction stage of construction projects. These apps empower construction site personnel to document changes promptly. For example, workers can use their mobile devices to take photos, record descriptions, and note relevant details of any change on-site. This immediate documentation ensures the accuracy and timeliness of data, which is essential for processing change visas accurately.

Simultaneously, these apps can be integrated with cost calculation algorithms. Once the change details are input, the app can quickly calculate the potential cost impacts, such as additional material costs, labor hours, or equipment expenses. By providing real time cost estimates, project managers can make informed decisions regarding the change. If the cost impact is too high, they may explore alternative solutions or negotiate with relevant parties. This kind of mobile based reporting not only streamlines the change management process but also enhances the precision of dynamic cost control, ultimately contributing to the successful delivery of construction projects within budget [13].

5.3. Case study analysis

5.3.1. Project background and implementation process

Take a large-scale infrastructure project as an example. This project was a crucial transportation related construction, aiming to improve regional connectivity. The initial plan was to construct a high-speed railway line across multiple regions, with a total length of over 300 kilometers.

The project kicked off with detailed pre construction planning. Surveyors spent months mapping the terrain, analyzing geological conditions, and identifying potential environmental impacts. Once the site-specific information was gathered, the design team started to develop the construction blueprints, taking into account various factors such as load bearing capacity, speed requirements, and safety standards.

During the implementation process, the project faced several challenges that led to change visas. For instance, unforeseen underground water sources were discovered in some sections, which required immediate adjustments to the foundation construction plan. This led to a change visa, altering the construction methods and materials. Another situation was when local residents raised concerns about the noise impact of the construction, resulting in additional requirements for noise reducing measures, thus causing another change visa.

The project team closely monitored these changes and their associated costs. They set up a real time cost tracking system that updated cost data daily. Key milestones in the implementation included the completion of the foundation work, the erection of bridge piers, and the laying of tracks. Each milestone was carefully reviewed to ensure that the project was on track in terms of both progress and cost control. This case clearly shows the practical application of change visa management and dynamic cost control in a large-scale infrastructure construction project.

5.3.2. Performance metrics and cost savings

The case study focuses on quantifiable performance metrics to demonstrate the effectiveness of change visa management and dynamic cost control. A key metric is the reduction in change processing time. In the project under study, an 18% decrease in change processing time was achieved. This was crucial as it minimized project delays. Swift processing of change visas ensured that any necessary adjustments to the construction plan could be implemented promptly, preventing idle time for construction teams and potential rework due to extended waiting periods.

Cost overrun mitigation is another vital performance metric. The project managed to mitigate cost overruns by 12%. This was accomplished through strict review and control of change visas. Each change was carefully evaluated for its necessity and cost implications. By doing so, unnecessary changes that could have inflated costs were avoided. For example, alternative solutions were explored to meet project requirements without incurring excessive expenses.

Improved audit compliance rates also signify effective management. A higher audit compliance rate indicates that the change visa management and cost control processes adhered to relevant regulations and internal policies. This not only reduces the risk of legal issues but also enhances the overall credibility of the project. These performance metrics and cost savings clearly illustrate the positive impact of effective change visa and dynamic cost control measures in the construction stage of construction projects.

6. Conclusion

In conclusion, the integration of dynamic cost control with systematic change visa management in the construction stage of construction projects has demonstrated remarkable transformative potential. Through this approach, significant efficiency gains have been achieved, such as streamlined decision making processes regarding change visas. This not only reduces unnecessary delays but also optimizes resource allocation, ensuring that projects are completed within the planned schedule.

Value preservation in project delivery is another crucial outcome. By closely monitoring and controlling costs in real time during the change process, potential cost overruns are effectively mitigated. This ensures that the final project cost aligns with the budget, safeguarding the economic viability of the project.

Looking ahead, future research could focus on AI enhanced change prediction. AI technologies, with their ability to analyze vast amounts of historical data, can potentially predict changes more accurately. This would enable project teams to anticipate and prepare for potential changes in advance, further enhancing cost control and project management.

Blockchain based audit trails also present an exciting area of exploration. The immutability and transparency of blockchain can provide a secure and reliable record of all change visas and cost related transactions. This would enhance accountability, streamline auditing processes, and reduce the risk of fraud, thereby contributing to more effective project management in the construction industry. Overall, these future research directions hold great promise for further improving the management of change visas and dynamic cost control in construction projects.

Disclosure statement

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Research and Application of Building Engineering Intelligent Review System Based on BIM and Rule Engine

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Abstract: The research aimed to construct an intelligent review system for construction projects based on Building Information Modeling (BIM) and rule engines. By establishing a BIM data standard system and utilizing Structured Naming Language (SNL) to formalize review rules, combined with model visualization and scene recognition technology, a cloud native platform with automated review capabilities has been developed. The pilot application shows that the system can effectively improve the efficiency and accuracy of planning and construction drawing review, providing a feasible technical solution for digital engineering review.

Keywords: Building Information Modeling (BIM); Rule engine; Intelligent review

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1. Introduction

With the deepening implementation of the "14th Five Year Plan" for the development of the construction industry and the announcement of the list of pilot cities for intelligent construction by the Ministry of Housing and Urban Rural Development in 2022, promoting the digital transformation and intelligent upgrading of the construction industry has become a clear direction for industry development. The traditional construction project review mode highly relies on manual interpretation of two-dimensional drawings, which has problems such as low efficiency, inconsistent standard implementation, and easy omissions, making it difficult to meet the higher requirements of modern construction industry system for quality and efficiency. Building Information Modeling (BIM) technology, as an important carrier of engineering digitization, has provided the possibility for achieving automation and intelligence in the review process. However, achieving machine understandable and executable expression of normative provisions, and building a review system capable of automatic reasoning and recognition, remains the core technical challenge currently faced. Therefore, researching intelligent review systems based on BIM and rule engines has urgent practical significance for implementing national intelligent construction policies, improving engineering review efficiency, and ensuring engineering quality and safety.

2. Overall architecture design of BIM intelligent review system

2.1. System architecture design principles

The architecture design of this system follows the principles of cloud native and modularization, ensuring that the platform has high scalability, flexibility, and reliability. The system is centered around microservices, encapsulating core capabilities such as data management, model parsing, and rule engines as independent services to achieve loose coupling and on-demand deployment of services. Openness is an indispensable principle, and the system supports international common data formats such as IFC, and is committed to cloud based lossless parsing and integration of multi-source heterogeneous BIM models, breaking the dependence on specific modeling software. This is in line with the requirements for data integration and interoperability in the optimization of digital review processes for construction drawings [1]. In terms of technical architecture, knowledge graphs are used as the underlying storage and organization method for BIM data, revealing the complex relationships between components through semantic modeling, providing an efficient data query and relationship reasoning foundation for intelligent review. Security runs through the entire design process, with full process permission control and operational traceability of model data to ensure the integrity and immutability of data during circulation and review.

2.2. Division of system functional modules

The system is divided into seven core functional modules based on the intelligent review business process. The BIM data standard service module is responsible for maintaining unified classification codes, attribute sets, and delivery standards, providing benchmarks for model quality. The model parsing and conversion module undertakes the cloud based lightweight parsing and conversion tasks of multi format BIM models, and outputs unified structured data. The model visualization and rendering module provides lightweight browsing, interaction, and linkage functions for web-based 2D and 3D models. The review rule engine module is the intelligent core of the system. Based on structured SNL rule descriptions, it performs automatic compliance checks and logical reasoning. Its precise analysis and execution of professional provisions such as fire safety regulations are the key technical support for achieving efficient and accurate review [2]. The review scenario management module utilizes graph technology to achieve pre identification and tagging of review scenarios, improving the efficiency of rule matching and review. The review result management and reporting module visualizes, categorizes, and generates reports on the review results. The system integration and interface module provides a standardized channel for data exchange and business process integration between the platform and external systems, such as CIM platform, project management system.

3. BIM data standards and model processing techniques

3.1. Construction of BIM data standard system

The BIM data standard system is the cornerstone for ensuring information interoperability and automated review. The system is built around a unified component classification and coding rule, clarifying the identification and organizational logic of various model elements. The attribute parameter standard defines inherent information such as material and size of components, and extends the attributes that need to be filled in by the design end, standard attributes directly extracted from the model, and derived attributes obtained through geometric and business rule deepening calculations. The definition of these calculated attributes is crucial for achieving automated review of architectural design specifications [3]. The model geometry standard standardizes the geometric representation methods and spatial relationships of components, ensuring visual consistency and computational accuracy of the model. The data format and exchange standards have established an open data environment centered around

IFC, supporting cross platform, full lifecycle information lossless transmission. This comprehensive standard framework provides a unified data specification for model quality assessment, engineering quantity statistics, and full process collaboration, which is a prerequisite for achieving intelligent review.

3.2. Cloud parsing and storage technology for multi format models

Faced with multi-source heterogeneous BIM model data, cloud parsing technology is committed to achieving format generalization processing that is decoupled from the native modeling software environment. The core of this technology is to deeply parse the data structures and encoding methods of mainstream formats such as RVT and DGN, and convert them into a unified intermediate data format within the system. Synchronize the simplification and optimization of model data during the parsing process, and improve network transmission and parsing efficiency by removing redundant information, optimizing data organization and compression techniques. At the data storage level, the system breaks through the limitations of traditional relational databases or pure file storage, explores the lightweight and flat transformation of IFC standards, and innovatively adopts knowledge graph technology for the organization and management of BIM data. This graph-based storage maps components, attributes, and their complex relationships to nodes and edges, providing efficient support for semantic based complex queries, rapid extraction of sub models for business scenarios, and deep relational reasoning. To ensure the security and credibility of data during this process, distributed ledger technology can be introduced to authenticate key operations and enhance the credibility of review results, thereby greatly improving the flexibility, security, and intelligence level of data utilization [4].

4. Rule engine and intelligent review method

4.1. Structured expression of multiple review rules

4.1.1. Specification description method based on SNL

To achieve machine-readable and executable functionality, the review rules are formally described using Structured Naming Language (SNL). This method converts design specifications written in natural language into standardized computer statements, clearly defining the types of components, key attribute requirements, and spatial and logical relationships that must be satisfied between components in the model. For example, the review provisions for fire separation distance can be transformed into logical assertions that measure and compare the geometric positional attributes of specific component categories (such as walls, doors, and windows). This unified description format based on SNL provides precise and error free instruction input for the review rule engine, which is the core technical foundation for achieving a leap from manual interpretation to automated and intelligent review. Its purpose is to solve the efficiency bottleneck and subjective deviation problems caused by relying on manual item by item verification in the traditional review process, ensuring the consistency and ambiguity of machine understanding of normative provisions [5].

4.1.2. Construction and management of review rule library

The construction of the review rule library began with a systematic review of mandatory provisions and industry standards in stages such as reporting for construction and construction, and reviewing construction drawings. Collaborating with experts in the professional field and BIM engineers, the selected articles are translated and structured using SNL language to form an initial set of atomic rules. The rule library adopts a hierarchical classification architecture for management, which can be organized in multiple dimensions based on professional fields (such as architecture, structure, fire protection), applicable stages, and regulatory sources, supporting efficient retrieval and reuse of rules. The rule library management system provides version control, state management, and dependency analysis functions for rules, ensuring that relevant rules can be quickly located and iterated during specification updates, maintaining the timeliness and accuracy of the rule library. This systematic rule management mechanism is crucial for responding to dynamic updates of normative provisions and ensuring the authority and compliance of review criteria [6]. It is an institutional guarantee for the reliable operation and industry recognition of intelligent review systems, providing dynamic knowledge support for the continuous evolution of intelligent review.

4.2. Review the scene recognition and reasoning mechanism

4.2.1. Scene feature extraction and tagging

The foundation of reviewing scene recognition lies in transforming complex review articles into computable scene features. By deeply analyzing the semantics of the text, extracting the professional fields involved, target component types, key attribute constraints, and spatial or logical relationships between components, a feature triplet centered on "subject relationship object" is formed. These features define specific review contexts, such as "evacuation stairs–minimum net width–greater than or equal to the specified value". After uploading the model, the system scans and matches the BIM model based on a predefined scene feature classification system, identifies local parts of the model that match specific feature combinations, and automatically attaches corresponding scene labels to them. This tagging process logically aggregates originally scattered components based on review intent, laying the foundation for subsequent targeted and efficient rule execution. Its effectiveness has been verified in practical projects such as the Nanjing Construction Drawing BIM Intelligent Review System, significantly improving the automation level of review [7].

4.2.2. Model mapping and review reasoning

The effectiveness of scene recognition heavily relies on the graphical representation of BIM models. Model visualization transforms traditional BIM data into a semantic network consisting of "nodes" (representing component instances) and "edges" (representing relationships between components). This transformation explicitly expresses and stores complex relationships such as component properties, spatial topology, and system associations. In the review reasoning stage, the rule engine does not need to directly process the original geometric model, but operates on the labeled scene subgraphs. The engine traverses nodes and edges in the graph to verify whether their attributes meet the conditions specified by SNL rules, and uses graph query and inference algorithms to discover implicit associations and conflicts. For example, by analyzing the topological relationship between fire zones and evacuation routes, automatic inference of whether evacuation distances are compliant can help systematically identify and warn of complex spatial logic problems that are easily overlooked in traditional manual reviews [8]. This graph-based reasoning mechanism significantly enhances the ability and efficiency of reviewing complex spatial and logical relationships.

5. System implementation and pilot applications

5.1. Development of BIM intelligent review platform

5.1.1. Implementation of platform core function modules

The platform is based on a microservice architecture and integrates seven core functional modules to support the entire process of intelligent review. The data standard service module maintains component classification, coding, and attribute rules, providing a unified benchmark for model quality. The model parsing service realizes cloud conversion and lightweight processing of multi-source BIM formats, and outputs structured model data. The model rendering service provides online browsing and interaction capabilities for 2D and 3D models in a web environment. The rule engine service serves as the system brain, loading and executing structured review rules based on SNL language. The scenario management service utilizes knowledge graph technology to achieve automatic recognition and tagging of review scenarios. Review and analyze the coordination of various modules in the service, and perform specific compliance checks and conflict detection. The results reporting service visualizes the review results and generates structured review reports. Each module works together through standardized interfaces to form a complete automated review loop, marking a profound transformation of the construction drawing review mode from traditional manual led to intelligent and systematic direction [9].

5.1.2. Application of 2D and 3D graphic modeling linkage technology

To solve the problem of disconnection between 2D drawings and 3D models in traditional review, the platform has implemented deep 2D and 3D model linkage technology. This technology automatically extracts the type, position, and size information of components such as walls, doors, and windows in CAD drawings through drawing element recognition algorithms. Establish precise spatial correspondence between 2D graphics and 3D model components using coordinate mapping relationships. Reviewers can select specific elements on the 2D drawing, and the system automatically locates and highlights the corresponding model components in the 3D view, synchronously displaying all their attribute information. This technology not only greatly facilitates the consistency review of graphics and models, enabling the rapid detection and localization of design conflicts and expressions that do not match, but also provides an intuitive and efficient human-computer interaction interface for core review functions. This technology demonstrates significant advantages in dealing with specialized reviews involving complex spatial relationships, such as compliance verification of sponge city facility layout and vertical design. It can effectively assist reviewers in understanding design intent and verifying technical details, improving the accuracy and efficiency of the entire review process [10].

5.2. Pilot application and effect analysis

5.2.1. Pilot program for review of regulatory and construction applications

During the planning and application stage, the system conducted pilot applications for the issuance of construction project planning permits. The pilot focuses on automated verification of key planning indicators such as building area, building height, plot ratio, and green space ratio. The platform automatically extracts the geometric and attribute information of relevant components by parsing the BIM model submitted for construction, and performs indicator calculation and compliance comparison based on preset SNL rules. The application results show that the system can quickly and accurately complete the review of various planning and control indicators, transforming the large amount of repetitive work that originally relied on manual accounting into an automated process that can be completed in seconds. This not only significantly improves the efficiency of initial review of construction materials, reduces repeated modifications caused by human calculation errors, but also provides objective and quantitative technical review basis for planning and management departments, strengthening the scientific and standardized nature of planning and management.

5.2.2. Pilot project for construction model review

The pilot project for construction drawing review mainly focuses on compliance inspections with mandatory regulations such as fire safety, civil air defense, and structural safety. The platform has loaded a review rule library for local standards such as the “Design and Delivery Standards for Building Information Modeling”, which systematically reviews the integrity of BIM model components, design depth, and implementation of regulatory provisions during the construction phase. The pilot verified the effectiveness of the system in detecting common design issues such as integrity of fire compartments, insufficient evacuation width, and inadequate fire resistance limits of components. Through automated review, a large amount of basic and standardized specification clause inspection work can be efficiently completed, allowing reviewers to focus their energy on more complex engineering judgments and design optimization suggestions. This effectively enhances the comprehensiveness and accuracy of construction drawing review, providing a powerful technical tool for ensuring project quality and safety from the source.

5.3. System performance and economic benefit analysis

5.3.1. Achievement of main technical indicators

System performance is measured through a series of quantifiable technical indicators. In terms of model processing capability, the platform has successfully achieved cloud parsing and lightweight conversion of BIM models generated by mainstream software such as Revit and ArchiCAD, supporting smooth online browsing of GB level models. The rule engine has efficient reasoning ability and can complete rule matching and result output in seconds for typical review scenarios containing hundreds of components. The system supports concurrent user access and maintains response times in sub seconds, ensuring a collaborative review experience for multiple users. In terms of accuracy, the structured rule expression and graph-based reasoning mechanism based on SNL significantly improves the accuracy of the system's review of clearly defined normative provisions compared to traditional manual sampling, especially in the verification of spatial relationships and quantitative indicators, demonstrating stable and reliable performance.

5.3.2. Economic and social benefit evaluation

The application of this system has generated significant comprehensive benefits. At the economic level, automated review significantly reduces the time cost of manual verification of drawings and specifications, freeing reviewers from repetitive labor and focusing on higher value technical decisions, directly reducing the manpower investment and time cycle of project review. Early detection and correction of design errors have avoided rework and changes during the construction phase, resulting in significant indirect economic benefits. In terms of social benefits, the system has improved the standardization and transparency of the review process, enhanced the ability to control engineering quality, and helped prevent safety risks from the source. Its promotion and use have promoted the deep application of BIM technology and the digital transformation of the construction industry, providing key technical support for building a collaborative, efficient, and intelligent new construction model.

6. Summary

A set of intelligent review methods and technical systems based on BIM and rule engines have been systematically constructed to meet the practical needs of intelligent review in construction engineering. The research has established a system architecture centered on cloud native and openness, and developed BIM data standards covering component classification, attribute parameters, and data exchange, laying the foundation for information interoperability and automated review. By introducing SNL language to achieve structured description of review rules and combining knowledge graph technology for semantic storage and scene recognition of BIM models, the accuracy and efficiency of review reasoning have been effectively improved. On this basis, the BIM intelligent review platform developed integrates core functions such as multi format parsing, rule engine, and 2D/3D linkage, forming a complete review loop. The pilot application in stages such as planning and construction drawing review has shown that the system can significantly improve review efficiency and quality, reduce labor costs and error rates, and demonstrate good technical feasibility and application value. This research achievement provides a practical and feasible technical path and practical reference for promoting the intelligent transformation of construction project review, and has positive significance for promoting the digital development of the construction industry.

Disclosure statement

The author declares no conflict of interest.

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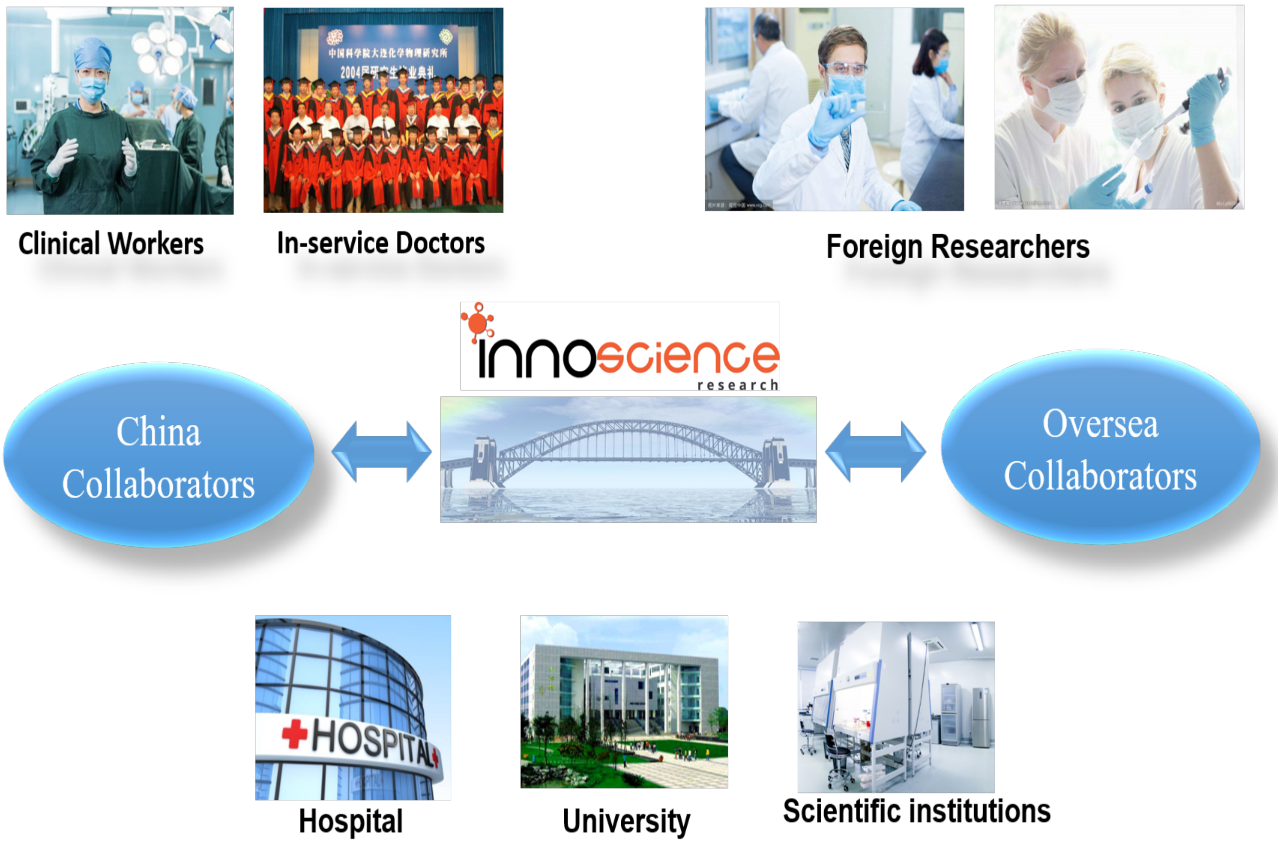

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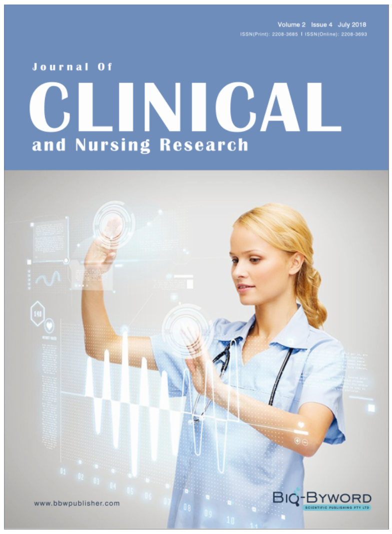

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The Practice of Biophilic Design in Indoor Space: Taking the Office as an Example

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Abstract: Biophilic design significantly enhances the ecological efficiency and humanistic value of office spaces by integrating natural elements with artificial environments. Studies show that this design can reduce building energy consumption by 15–20%, while increasing employee productivity by 12–18%. Key technical challenges include maintaining micro-ecological balance and cross-system collaborative control, and the lack of cost-benefit quantification tools hinders market promotion. As green building evaluation systems improve, intelligent environmental regulation technologies and standardized assessment methods will become key focuses for future development, providing scientific support for sustainable office environment construction.

Keywords: Biophilic design; Office space; Sustainable architecture

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1. Introduction

With the acceleration of urbanization, modern office environments are increasingly isolated from nature, leading to issues such as decreased employee mental health and reduced work efficiency. Biophilic Design, which integrates natural elements into architectural spaces to re-establish the connection between humans and nature, has become an important approach to improving indoor environmental quality [1]. The "14th Five-Year Plan for Building Energy Efficiency and Green Building Development" issued by the Ministry of Housing and Urban-Rural Development in 2023 clearly promotes the concept of green and low-carbon design, encourages the use of ecological building materials and natural ventilation and lighting technologies, and provides policy support for the application of Biophilic Design in office spaces [2]. Research has shown that introducing plants, natural light, and organic materials into offices can significantly enhance employee satisfaction and reduce carbon emissions, aligning with the sustainable development needs under the "dual carbon" goals [3]. Against this backdrop, exploring the practical strategies and benefits of Biophilic Design in office spaces is of great practical significance for promoting the construction of healthy buildings and low-carbon cities.

2. Theoretical basis of nature-friendly design

2.1. The connotation of nature-friendly design

The theoretical foundation of Biophilic Design stems from the "Biophilia Hypothesis" proposed by Wilson (1984) [4], which posits that humans have an innate emotional and physiological dependence on nature. This hypothesis reveals the deep influence of natural elements on human cognition, emotions, and behavioral patterns from an evolutionary psychology perspective [5]. Based on this, Biophilic Design reconstructs the connection between artificial environments and ecosystems by systematically integrating natural elements. This article is framed around "14 Biophilic Design Patterns" [6], with design elements divided into three major categories and fourteen subcategories: direct natural elements, such as physical interventions like vegetation, water bodies, and natural light; indirect natural metaphors, including abstract expressions like natural material textures, organic forms, and ecological colors; and spatial experience creation, which emphasizes simulating natural settings through techniques such as spatial sequence, visual transparency, and microclimate regulation (**Table 1**). These three categories of elements together constitute a multi-layered design intervention system, aiming to compensate for the lack of natural experience in modern architectural environments.

Table 1. Browning's 14 biophilic design patterns (Table source: redrawn by the author)

Design patterns	Design elements
Nature in space	1. Visual connections; 2. Non-visual connections; 3. Irregular sensory stimuli; 4. Heat and air flow; 5. Water body design; 6. Dynamic and diffused light; 7. Natural systems
Nature analogies	1. Natural forms; 2. Natural materials; 3. Complexity and order
Naturalistic space	1. Outlook; 2. Sanctuary; 3. Mystery; 4. Riskiness

2.2. The value of nature-friendly design in office environments

The application of nature-friendly design in office environments yields comprehensive benefits across multiple dimensions. From a psychological perspective, the introduction of natural elements can significantly reduce cortisol levels and alleviate cognitive fatigue through the Attention Restoration Theory (ART) mechanism, thereby enhancing creative output efficiency by 15–20% [7]. Physiologically, indoor plant communities can absorb more than 30% of volatile organic compounds (VOCs), and when combined with passive humidity regulation systems, they can maintain a relative humidity range of 40–60% that is optimal for human comfort [8]. Organizational behavior research shows that office spaces with nature-friendly design increase employee retention rates by 12–18%, and companies that have obtained LEED or WELL certifications exhibit significant advantages in attracting talent [9]. These benefits collectively constitute the intrinsic motivation for modern enterprises to adopt nature-friendly design, making it a core strategy for enhancing the quality of office spaces.

3. Key strategies for nature-friendly design in offices

3.1. Direct introduction of natural elements

The nature-friendly design of office spaces primarily achieves direct integration of natural elements through two approaches. In terms of plant configuration, vertical greening systems utilize modular planting units to facilitate space-efficient utilization. Ecological walls, combined with automatic irrigation technology, can establish a stable indoor micro-ecosystem. Meanwhile, mobile potted plant systems provide a flexible means of space division. Natural light optimization strategies emphasize passive design in architecture, with light wells using light-guiding technology to introduce natural light into deeper spaces.

High-transmittance glass partitions ensure visual connectivity while reducing the need for artificial lighting.

Intelligent dynamic shading systems automatically adjust based on the sun's angle, achieving optimal lighting and thermal comfort balance throughout the year. These technical measures collectively create an office environment with biophilic characteristics. Furthermore, the introduction of water features, such as indoor water curtain walls or small fountain systems, not only enhances the aesthetic appeal of the space but also regulates air humidity, enhancing the ecological perception of the environment. The use of natural materials, such as wood, stone, and bamboo, strengthens the connection between humans and nature both visually and tactually.

Natural ventilation strategies, utilizing operable window sashes, wind towers, or atrium designs, introduce fresh air and improve indoor air quality. These diverse technical measures collectively create an office environment with biophilic characteristics, effectively enhancing user comfort and work efficiency (**Table 2**).

Table 2. Direct incorporation of natural elements (Table source: drawn by the author)

Key strategies for biophilic office design	Implementation methods	Design elements
Direct integration of natural elements	Vertical greening	Visual connections;
	Portable potted plants	Visual connections;
	Light wells	Dynamic and diffused light;
	Smart shading systems	Dynamic and diffused light;
	Water walls, Mini fountains	Visual connections; Water body design;
	Natural materials	Natural materials; Visual connections;
	Wind towers, Atriums	Non-visual connections; Heat and air flow;

3.2. Indirect expression of natural imagery

In spaces where direct incorporation of natural elements is not feasible, meticulous design of colors and textures can still evoke natural associations in users. The application of earthy tones follows environmental psychology principles, creating a sense of stability with low-saturation colors such as warm grays, terracotta, and moss green. The color temperature is controlled within the range of 3000–4000K to simulate natural lighting effects.

The composition of organic forms draws on fractal geometry theory, breaking the mechanical feel of artificial environments through design languages such as asymmetric curves and irregular interfaces. In terms of material selection, recycled wood with natural textures and mineral coatings not only meet visual needs but also enhance the user's natural experience through tactile feedback [10].

Additionally, creating a soundscape is also an important approach. By introducing natural sound effects (such as flowing water and bird songs) or using materials with natural sound sensations (such as bamboo wind chimes), the ecological atmosphere of the space can be effectively enhanced.

Odor design is equally important. Utilizing natural plant essential oils or wood aromas can evoke memories of natural environments such as forests and grasslands, enhancing the natural affinity of the space. Simulating light and shadow effects can also enhance natural perception, such as using dynamic light projection technology to simulate the effect of sunlight passing through leaves, or using translucent materials to create a soft natural light sensation. These diverse indirect expression methods, while maintaining the functionality of modern office spaces, successfully incorporate ecological aesthetic values, further enhancing users' comfort and psychological pleasure (**Table 3**).

Table 3. Direct introduction of natural elements (Table source: drawn by the author)

Key strategies for biophilic office design	Implementation methods	Design elements
Indirect expression of natural elements	Earth tones	Visual connections;
	Natural textures	Visual connections;
	Color temperature of simulated Natural light	Visual connections;
	Organic forms	Natural forms;
	Wind chimes with natural Sound effects	Dynamic and diffused light;
	Natural plant essential oils	Irregular sensory stimuli
	Aromatic wood	Irregular sensory stimuli
	Soft translucent materials	Dynamic and diffused light

4. Case study on the practice of nature-friendly design in offices

4.1. Case studies of co-working spaces abroad

4.1.1. Case background: Second Home co-working space in London

Second Home, located in the Spitalfields area of East London, spans two floors and covers approximately 6,000 square meters. It stands as a typical example of biophilic office space design in recent years (**Figure 1**).

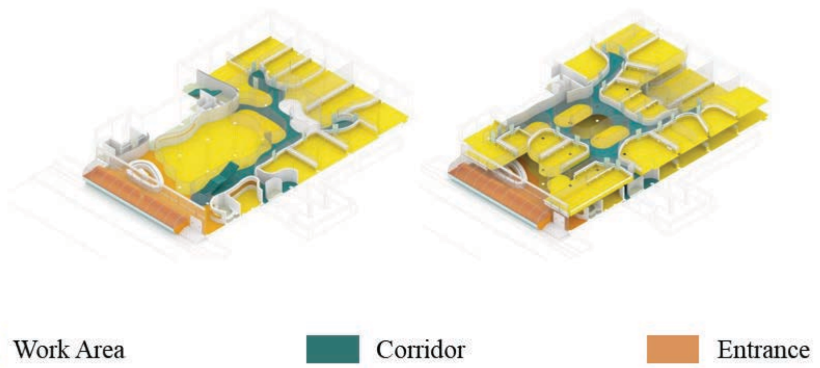

Figure 1. Ground and second floor plans (Image source: www.Archaily.com).

Its core objective lies in enhancing users' physical and mental health, as well as social interaction efficiency, through the deep integration of architecture and the natural environment. Distinct from traditional enclosed and mechanized office spaces, Second Home leverages natural light, abundant vegetation, and an organically flowing spatial layout to create an open and ecologically rich workplace. By introducing and integrating natural elements, this project not only fulfills individuals' physiological health needs but also enhances psychological pleasure and cognitive focus. Furthermore, Second Home has further expanded the connotation of biophilic design in terms of spatial organization and atmosphere shaping, transforming the office space into a "second home" that integrates ecology, creativity, and social interaction. Thus, this case exemplifies the trend of contemporary office environments shifting from functionality to humanism and sustainability.

4.1.2. Design highlights: deep integration of natural elements, dynamic optimization of environmental rhythms, and comprehensive enhancement of multi-sensory experiences

Firstly, in terms of the introduction of natural elements, the project extensively arranges green vegetation both indoors and outdoors (**Figure 2A**), giving the office environment the characteristics of an "urban oasis" or "indoor forest". This large-scale vegetation not only provides natural scenery at the visual level, but also plays a positive role at the physiological and psychological levels, helping to reduce stress levels, enhance emotional states, and increase happiness [11].

Secondly, the project has undergone refined design in terms of light environment and spatial rhythm. Through large-area floor-to-ceiling glass, skylights, and translucent partitions (**Figure 2B**), the indoor space is able to maximize the introduction of natural light, allowing users to perceive changes in day and night and seasons during daily office work. This infiltration of dynamic light and shadow not only improves the comfort of the space but also helps regulate the human body's biological clock, enhancing attention and productivity [12].

Furthermore, Second Home fully embodies naturalness and organicness in its spatial form and material selection (**Figures 2A and 2B**). The design abandons the straight and rigid layout typical of traditional office settings, opting instead for a curved and flowing spatial arrangement, coupled with organic materials such as natural wood and glass, creating a soft and warm spatial texture. This design not only enhances sensory comfort but also echoes the principle of "natural form and texture" emphasized in biophilic design [13].

Figure 2. The interior real scene photos. A. Integration of indoor and outdoor vegetation creating an "urban oasis" office environment; B. Use of natural lighting through floor-to-ceiling glass and skylights to enhance spatial rhythm and comfort. (Data source: www.Archaily.com).

4.2. Case of domestic enterprise headquarters

4.2.1. Case background: The headquarters of a real estate company

The project is located in the Economic and Technological Development Zone in the north of Langfang City, Hebei Province, on the north side of Xiangyun Road and the west side of Yuquan Road. The aboveground building area is 17,420.71 square meters, divided into three main office buildings: B, C, and D (with a standard floor area of 2,100 square meters for buildings B + C). The building height is ≤ 48 meters, serving as the headquarters building for the real estate company. The internal functions include customer service/intelligent capability operation center, lifestyle experience center, and a core focus on the company's advanced intelligent and ecological office concept. The project innovatively combines nature-friendly design with employee behavior and scenario-based creation, hoping to provide new ideas for corporate headquarters office spaces (**Figure 3 and Figure 4**).

Figure 3. Architectural rendering (Image source: Drawn by the author).

Figure 4. Standard floor plan of buildings B and C (Image source: Drawn by the author).

4.2.2. Design highlights: Disassembly and reference of natural elements, creation of scenes imitating natural elements

Firstly, the project fully utilizes the direct introduction and indirect expression of natural elements, breaking them down into four dimensions (**Figure 5**): vertical greenery (using broad-leaved plants such as turtle-back bamboo that are easy to grow in the north) can effectively reduce the sound and visual interference from dynamic spaces to static spaces; the use of natural-looking office carpets helps reduce employees' work pressure and enhance comfort; mobile flower beds can be used to flexibly divide spaces and be called upon as needed; desktop greenery can choose plants such as Pothos that are easy to maintain, increasing the green content of the space and enhancing the comfort of the office environment.

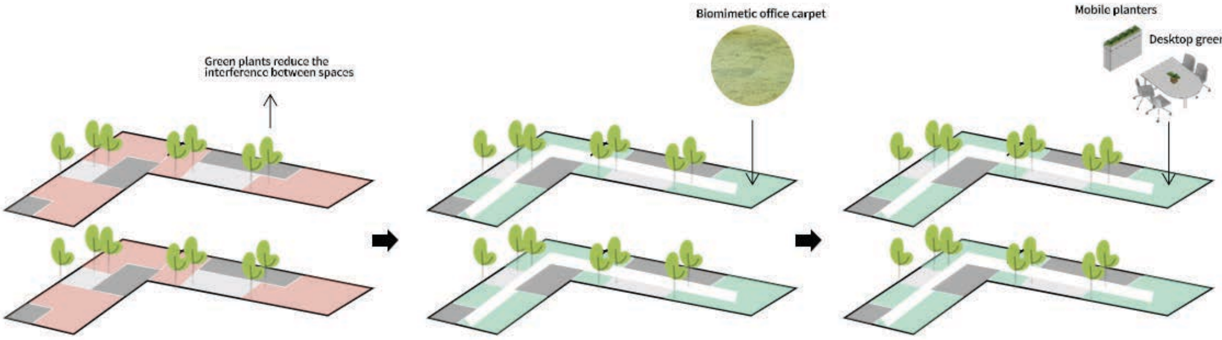

Figure 5. Incorporation of natural elements in the standard floor (Image source: Drawn by the author).

Secondly, the design utilizes natural wood-grain panels as the primary design element for the walls, combined with earth-toned paints for the ceiling and floor, as well as terrazzo, to simulate a natural indoor space. Furthermore, it incorporates linen carpets and locally green imitation grass carpets to distinguish different spatial attributes, complemented by organically shaped office furniture, creating various office scenarios that are conducive to employees' better value creation and work efficiency improvement (**Figure 6**).

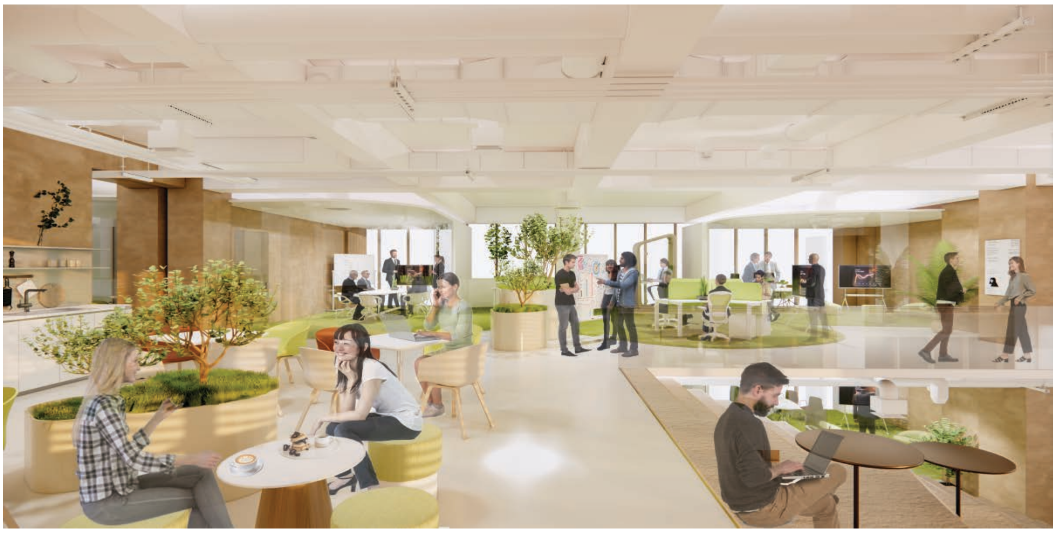

Figure 6. Biophilic design in the standard floor office (Image source: Drawn by the author).

5. Challenges and optimization paths in the implementation of nature-friendly design

5.1. Technical challenge

5.1.1. Plant maintenance and indoor microecological balance

The sustainable operation of indoor plant systems faces multiple technical bottlenecks. Shade-loving plants have reduced photosynthetic efficiency in low-light environments, necessitating the use of artificial light compensation systems, which leads to increased energy consumption. The air circulation in enclosed spaces is limited, and plant transpiration often causes humidity to exceed the human comfort range. The imbalance of microbial communities is particularly prominent, and the concentration of mold spores in soil substrates may exceed standards. Existing solutions include developing new soilless cultivation media, using nano-coatings to inhibit the proliferation of pathogenic bacteria, and introducing intelligent environmental linkage systems. However, these technologies still have drawbacks such as high cost or insufficient stability, which restrict their large-scale application [14].

5.1.2. Collaborative control of natural lighting and artificial lighting

The design of building lighting interface faces the contradiction between sunlight radiation and visual comfort, and glare is prone to occur when the visible light transmittance (VLT) of the curtain wall exceeds 40%. The existing lighting control systems mostly use single factor adjustment of illumination, which is difficult to adapt to the lighting environment requirements of different work scenarios [15]. The new light environment management system achieves dynamic matching of natural lighting and LED supplementary lighting through a distributed illuminance sensor network and a working face illuminance demand model. However, the system has technical defects such as response delay (about 2–3 seconds) and abrupt regional transitions, and the high-precision sensor array increases the initial cost by 25–30%, which restricts the popularization of technology [16].

5.2. Coordinated control of natural lighting and artificial lighting

5.2.1. Economic challenges

The initial investment in nature-friendly design is 20–35% higher than that of traditional solutions, primarily due to the procurement of ecological materials (such as a 40% premium for FSC certified wood) and the deployment of intelligent systems [17]. The comprehensive cost of a vertical greening system reaches 3,000–5,000 yuan per square meter, and the payback period is usually over 5 years [18]. However, a full life cycle assessment shows that through reduced energy consumption (saving 15–25% annually) and improved employee efficiency (equivalent to 3–5% of annual labor costs), the investment payback period can be shortened to 3–4 years [19]. The current market lacks standardized assessment tools, making it difficult for owners to quantify potential benefits when making decisions, which hinders project financing. Establishing a comprehensive cost-benefit analysis model has become crucial for promoting the implementation of this technology.

5.2.2. Supply chain constraints of low-carbon materials

The current low-carbon building materials market faces severe structural contradictions between supply and demand. The production capacity of recycled building materials that meet EPD certification can only meet 15% of the market demand, resulting in a 60–90 days extension of the delivery cycle [20]. The problem of regional supply imbalance is prominent, and the transportation of low-carbon concrete prefabricated parts from the western region to the eastern coastal region actually increases the carbon footprint. The material certification system is highly fragmented, and the varying requirements for recycled material content in standards such as LEED and BREEAM make it difficult for manufacturing enterprises to achieve large-scale production, severely restricting the standardized promotion of nature-friendly design.

5.3. Optimization of design methodology

5.3.1. Quantitative assessment tools: Such as the nature-friendly indicators in the WELL building standard

The current evaluation system still has significant limitations in the quantitative evaluation of pro natural design. Although the WELL v2 standard establishes the concept of “natural systems” (Feature X05), its seven scoring indicators only cover 30% of biologically friendly environmental elements. Especially for the evaluation of spatial sequences and natural rhythms, there is a lack of objective parameters, mainly relying on subjective scores from experts. The emerging digital assessment tools attempt to establish a mathematical model of the correlation between alpha wave activity and natural elements through EEG monitoring and eye tracking technology, but the sample size is insufficient, resulting in low reliability and validity. Developing an intelligent evaluation platform that integrates physiological feedback and building parameters has become a key breakthrough direction for improving the scientificity of design.

5.3.2. Interdisciplinary collaboration: The Integration of architecture, environmental psychology, and IoT technology

The deepening of pro nature design urgently requires the construction of interdisciplinary collaboration frameworks. The architectural spatial form parameters (such as window to ground ratio and line of sight transparency) need to be quantitatively correlated with the stress threshold model (cortisol level < 15 **μg**/dL) used in environmental psychology research. The IoT sensor network can collect 12 environmental data in real-time, including CO_2 concentration (maintaining < 800 ppm) and light intensity (300–500 lux), but there are protocol incompatibility issues in multi-source information fusion. Digital twin technology provides a new path for interdisciplinary collaboration, integrating biometric data and building performance simulation through BIM platforms. However, the current efficiency of data exchange among various disciplines is insufficient. Establishing a unified data standard and collaborative design platform is the key to breaking through disciplinary barriers.

6. Conclusion

The application of nature friendly design in office spaces has evolved from a simple aesthetic pursuit to a systematic engineering that integrates environmental performance and humanistic care. Practice has shown that the intervention of natural elements in science can increase work efficiency by 12–18% and reduce building energy consumption by 20–30% [21]. The current technological bottleneck mainly focuses on the precision of microenvironment control and cross system collaboration, while the standardization of cost-benefit analysis will directly affect market acceptance. With the inclusion of biodiversity indicators in the scoring system of the "Green Building Evaluation Standards" (GB/T50378-2023), it is necessary to focus on breakthroughs in dynamic environmental optimization algorithms supported by digital twin technology in the future. The development of this field is not only related to the improvement of building performance, but also an important practice for reconstructing the symbiotic relationship between humans, buildings, and nature.

Disclosure statement

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Study on Problems and Countermeasures in the Construction of Warping Dam Projects in the Loess Plateau Area

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Abstract: In recent years, to better address soil erosion, the Loess Plateau area has seen a surge in the construction of warping dam projects. Warping dams have strong functions in soil and water conservation as well as warping for farmland creation, serving as a key support for ecological restoration and economic development in the Loess Plateau area in the new era. However, in light of practical conditions, there are many problems in their construction process, which have affected their actual operation quality. In this regard, while expounding on the value and significance of warping dam project construction in the Loess Plateau area, this paper discusses the existing problems and effective countermeasures, aiming to provide some references for relevant personnel.

Keywords: Loess plateau; Warping dam project; Value and significance; Existing problems; Effective countermeasures

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1. Introduction

The Loess Plateau spans multiple provinces and autonomous regions in China, covering an area of 640,000 square kilometers. Due to natural characteristics such as thick loess layers, low vegetation coverage, and concentrated precipitation, it has become one of the regions with the most severe soil erosion in the world. Relevant data show that the annual soil erosion volume in the Loess Plateau is about 1.6 billion tons. This not only affects the local soil fertility and leads to land degradation but also directly causes sedimentation in the lower reaches of the Yellow River, posing hidden dangers such as floods and waterlogging disasters, which directly impact local social security and economic development. Warping dam projects, which began in the 1950s, integrate functions such as soil and water conservation, flood prevention and disaster reduction, and warping for farmland creation, and have gradually become an important "lifeline" for ecological management in the Loess Plateau [1]. At present, although warping dam projects are constantly being constructed and innovated, there are still problems such as unscientific planning and design and uneven construction quality, which directly affect the ecological environment protection and development of the Loess Plateau area [2]. In this regard, it is imperative and timely to actively explore the countermeasure paths for the construction of warping dam projects in the Loess Plateau area in the new era.

2. The value and significance of warping dam project construction in the loess plateau area

2.1. Ecological value: Consolidating the barrier for regional soil and water conservation and ecological restoration

For a long time, the Loess Plateau area has been facing severe soil erosion. Warping dam projects themselves have the functions of “blocking, storing, and silting”, which are of great significance for soil and water conservation in the Loess Plateau [3]. From the perspective of sediment interception, a single warping dam project can intercept 2,000 to 5,000 tons of sediment annually, which can effectively alleviate the problem of sedimentation in the lower reaches of the Yellow River [4,5]. From the perspective of water storage, the project can convert surface runoff into water resources, which can effectively improve the local water source conditions and promote the hydrological cycle. In addition, the project can promote the improvement of the local microclimate. For example, it can use functions such as water storage of the dam body to form a small wetland ecological environment, promote the growth of local herbs, shrubs and other plants, and improve the local ecological environment [4].

2.2. Economic value: Promoting sustainable agricultural development and rural economic growth

Affected by factors such as poor soil and uneven precipitation, agricultural production in the Loess Plateau area lacks stability. The advancement of warping dam projects can effectively improve this situation. On the one hand, it can increase soil fertility through “blocking, storing, and silting”, which effectively promotes the sustainable development of the local agricultural economy. On the other hand, compared with other lands, the dam land created by the project is rich in humus, which can effectively increase crop yields and lay a solid foundation for local food security. In addition, the construction and development of the project have also brought new opportunities for the development of local characteristic agriculture. For example, in the process of warping dam project construction in areas such as Yulin, Shaanxi, industries such as jujube and apple planting have been vigorously developed, which has effectively increased the income level of local farmers and injected new impetus into the development of the local rural economy [6].

2.3. Social value: Supporting rural revitalization and coordinated regional development

The construction of warping dam projects not only increases soil fertility and improves the yield of local food crops, but also promotes the “leveling” transformation of cultivated land, laying a solid foundation for the development of agricultural mechanization. Through the application of agricultural machinery, the efficiency of local agricultural production has been significantly improved [7]. At the same time, the project can also conserve local water sources, which can effectively solve the problem of domestic water use for local farmers. In addition, under the background of the project construction, industries such as rural tourism and rural e-commerce in the Loess Plateau area are developing vigorously, which also promotes the continuous upgrading of the agricultural industry and provides an important driving force for the implementation of the rural revitalization strategy and coordinated regional development.

3. Problems in the construction of warping dam projects in the loess plateau area

3.1. Planning and design level: lack of systematicness, scientificity, and poor adaptability

Scientific engineering planning and design are important foundations for ensuring the quality of warping dam projects. However, current warping dam projects in the Loess Plateau have problems such as insufficient systematicness, scientificity, and adaptability in planning and design, which affect the project quality and function performance. For example, in some river basin areas, the local river basin hydrological conditions are not fully considered during the construction of warping dams, and the distance design between dam bodies is unreasonable. This directly increases the local flood risk [8]. At the same time, the dam body coverage is insufficient in some areas. The existence of such “blind spots” poses great challenges to the overall soil and water conservation work. In addition, some warping dam designs adopt a “one-size-fits-all” approach, and the parameter design is not combined with local actual conditions. This leads to insufficient adaptability of the project and affects its actual function performance.

3.2. Project construction level: Uneven construction quality and ununified construction standards

At present, construction quality issues are prominent in the construction of warping dam projects in the Loess Plateau. On the one hand, construction units have problems such as simple equipment and unreasonable construction processes, resulting in substandard quality of warping dams. On the other hand, some construction units do not do a good job in controlling the quality of raw materials, such as using low-quality raw materials. This directly affects the quality of warping dams. In addition, the problem of ununified construction standards is also widespread. There are certain differences in relevant construction standards among different provinces, autonomous regions, cities, and counties. For example, the dam height standards in some areas are inconsistent with those in other areas. This situation not only affects the actual quality of warping dams but also brings certain difficulties to subsequent project acceptance and maintenance management [9].

3.3. Operation and management level: Imperfect management and protection mechanisms, and lagging post-maintenance

High-quality operation and management are the key to ensuring the effective operation of warping dam projects. However, current warping dam projects in the Loess Plateau generally have the problem of “emphasizing construction while neglecting management”. For instance, some areas do not attach importance to the subsequent operation and management after the completion of warping dams, nor do they establish special departments for supervision and maintenance. This causes some warping dams to suffer from severe sedimentation within 3 to 5 years after completion, affecting the performance of their soil and water conservation functions [10]. Secondly, there are also problems in post-maintenance. For example, there is a lack of sufficient fund planning, the channels for social participation in maintenance and management are not fully utilized, and the enthusiasm of the masses to participate in management is insufficient. These factors all affect the effective operation of warping dams.

3.4. Monitoring and early warning level: Imperfect monitoring system and weak risk prevention and control capabilities

Currently, the layout of warping dam monitoring stations in the Loess Plateau is not reasonable. They are mainly concentrated around some key river basins or large-scale warping dams, failing to achieve full coverage. This leads to inadequate monitoring during the subsequent operation of the dams. In addition, the risk response system for warping dams is imperfect in some areas. On the one hand, monitoring personnel still use manual inspection methods to collect and analyze data, which has obvious shortcomings such as poor timeliness and long cycles. This affects the actual risk prevention and control capabilities. On the other hand, due to the lack of scientifically designed emergency plans, the risk prevention and control as well as emergency response capabilities of warping dam projects in some areas are insufficient. This seriously affects the quality and function performance of warping dam projects.

4. Effective countermeasures for the construction of warping dam projects in the loess plateau area

4.1. Improve the planning system to realize the unity of “scientific layout” and “precise design”

Establishing a planning mechanism of “basin overall planning + regional adaptation” is the key to solving the planning and design problems of warping dam projects in the Loess Plateau area [11]. To this end, the overall plan for warping dam project construction should be formulated based on the conditions of the Yellow River tributaries. During this process, the construction scale, standards, and goals of warping dam projects in different river basins and regions should be clarified to implement the concept of “scientific layout”. For example, in river basins with severe soil erosion such as the Wuding River, a “cascaded dam system” design should be adopted to increase the construction density of warping dam projects, thereby further highlighting their value in soil and water conservation. Secondly, systematic survey work should be carried out. For instance, a dedicated survey team can be organized to conduct detailed surveys and analyses of the hydrology, geomorphology, soil, climate, and other environmental conditions in the construction area. On this basis, warping dam projects that match and coordinate with the above factors should be built to ensure the scientificity and forward-looking nature of the project construction.

In addition, technologies such as BIM and artificial intelligence can be used to conduct model simulation and analysis for warping dam construction during this process, thereby further improving the adaptability and scientificity of the project construction [12]. Furthermore, the integration of warping dam projects with local industrial development should be considered. During the design process, full cooperation and planning with local agricultural, tourism, and other departments should be carried out to align the construction of warping dam projects with the advancement of the local rural revitalization strategy. For example, in areas with strong tourism development potential, facilities such as viewing platforms and running tracks can be planned and designed around warping dam projects to better meet the needs of local industrial development, maximize the radiating effect of warping dam projects, and achieve the goals of precise design and multi-party win-win.

4.2. Strengthen construction supervision to promote the coordination of “quality control” and “standard specification”

First, the access mechanism for construction units should be improved. For example, construction units must have relevant project experience or qualification to contract Grade III or above projects, and possess professional equipment and talents. This approach can effectively ensure the construction quality of warping dams. During the construction process, “third-party testing” can also be introduced to conduct full-process supervision of the construction process and ensure that the construction quality meets the standards. Secondly, the raw material quality inspection system should be improved. The application of raw materials in the construction of warping dams should be supervised throughout the process. Once quality problems are found, responsibility tracing should be carried out immediately.

On this basis, the scientificity and safety of raw material inventory should be ensured. For example, during the storage of cement, the warehouse should be treated to be rainproof and moisture-proof to ensure the quality of raw materials and their effective use in subsequent processes. Furthermore, the construction acceptance standards should be improved. Relevant departments can take the lead in accelerating the issuance of documents on the construction quality and acceptance standards for warping dams in the Loess Plateau, and clearly stipulate the quality indicators and technical requirements of the projects to ensure the construction quality of warping dam projects [13]. On this basis, attention should be paid to the dynamic update of standards. For example, relevant standards and specifications should be dynamically adjusted based on local climate change and technological development in the new era to comprehensively improve their timeliness and scientificity.

4.3. Optimize the management and protection mechanism to promote the combination of "responsibility implementation" and "fund guarantee"

First, it is necessary to clarify multiple management entities and further define the responsibilities of entities at all levels. For example, a diversified warping dam management and protection model can be established, with government departments as the leading force, village collectives as the main responsible parties, and professional institutions extensively participating. This model can give full play to the management and protection efficiency of multiple entities. On this basis, the specific responsibilities of each entity should be clarified. For instance, relevant government departments are responsible for regularly assigning professionals to conduct dam inspection work to prevent potential risks. Village collectives can set up their own dam protection teams to take charge of the daily maintenance and management of warping dams. Professional institutions such as water conservancy management departments can provide professional technical services for the repair and maintenance of warping dams. Second, it is essential to improve fund guarantees.

Relevant government departments should establish a stable fund investment mechanism based on the actual situation of warping dam construction in the Loess Plateau. At the same time, they should actively encourage social capital to participate in the construction, management, and protection of warping dams. Relevant enterprises or individuals should be allowed to develop characteristic tourism, agriculture, and other industries around warping dam construction. This can better expand fund sources and give play to the role of warping dam projects in promoting local agricultural economic development [14]. Furthermore, the supervisory role of the masses should be fully exerted to ensure that multiple entities fulfill their duties and minimize the safety risks of warping dams. During this process, it is necessary to strengthen publicity and education for the masses. Village radio broadcasts, self-media communication, and other methods can be used to popularize knowledge about the construction, management, and protection of warping dams among local people. This will enhance their awareness of management, protection, and supervision, and create a good atmosphere where "everyone participates in management and protection, and everyone supervises management and protection".

4.4. Improve monitoring and early warning to realize joint efforts of "real-time monitoring" and "risk prevention and control"

To address problems in monitoring and early warning, the construction of warping dam projects in the Loess Plateau should continuously improve the monitoring and early warning mechanism. First, it is necessary to optimize the layout design of monitoring points to ensure full coverage. On this basis, digital technologies should be actively introduced to improve the timeliness and flexibility of monitoring and early warning. At the same time, modern digital platforms should be used to realize real-time sharing of warping dam monitoring and early warning information. This can avoid the problem of information silos that existed in previous manual monitoring and early warning [15]. Second, it is important to improve monitoring indicators and focus on comprehensive project benefit evaluation. For example, comprehensive monitoring and analysis should be conducted on local soil and water conservation, agricultural economic development, and other aspects. This will form a comprehensive monitoring report and lay an information foundation for the optimization and improvement of warping dam project construction.

Furthermore, it is necessary to optimize and upgrade the early warning system and early warning plans. For instance, a digital automatic early warning system can be introduced to monitor the operation status of warping dam projects in real time. An intelligent analysis system can be adopted to conduct intelligent analysis of monitoring data, detect potential risks in a timely manner, and then carry out effective handling and response.

In addition, it is also necessary to design and improve emergency plans, formulate early warning mechanisms for various emergencies and risks, clarify relevant handling procedures and main responsibilities, and regularly organize multiple entities to carry out emergency drills. This can comprehensively improve the coordination effect of various entities in risk prevention and control and effectively reduce the incidence of risk problems.

5. Conclusion

In general, there are certain practical problems in the construction of warping dam projects in the Loess Plateau area in the new era. In this regard, while scientifically analyzing these problems, we should constantly use new methods and countermeasures to improve the scientificity and effectiveness of warping dam project construction. This will enable warping dam projects to better play their roles and values, and lay a solid foundation for the realization of harmonious coexistence between humans and nature in the Loess Plateau area.

Disclosure statement

The author declares no conflict of interest.

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Stability Analysis and Safety Evaluation of Surrounding Rock in Shallow-buried Concealed Tunnel Construction

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Abstract: In the construction of shallow-buried concealed tunnels, the control of surrounding rock stability is a core challenge, which is crucial to construction safety and structural performance. A two-dimensional model was established using Midas GTS NX, combined with bench cut method excavation simulation. The laws of vault and surface settlement were quantitatively analyzed through displacement nephograms, and the spatiotemporal characteristics of surrounding rock displacement were revealed. The results show that under the established excavation and support measures, the displacement and settlement meet the specification requirements. Meanwhile, the Analytic Hierarchy Process (AHP) was introduced to determine weights and analyze the coupling correlation of factors through judgment matrices, clarifying the influence degrees of surrounding rock grade, support strength, and other factors to achieve multi-dimensional evaluation. Furthermore, the Fuzzy Comprehensive Evaluation method was integrated to quantify the mapping relationship between surrounding rock stability and safety, and the safety grade was obtained. Finally, measures such as strengthening support, optimizing excavation parameters, refined exploration, and improving management were proposed to enhance surrounding rock stability and reduce construction risks.

Keywords: Shallow-buried concealed excavation; Surrounding rock stability; Bench cut method; FAHP

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1. Introduction

In the construction of shallow-buried concealed tunnels, controlling surrounding rock stability is a core challenge that is critical to construction safety and structural performance. The shallow burial depth renders the surrounding rock mechanically vulnerable, and excavation is prone to inducing vault settlement and surface deformation. If surface settlement exceeds the allowable limit during construction, it will not only affect the flatness of hub functional areas or the construction accuracy of ongoing facilities but may also lead to construction suspension for remediation, resulting in project delays and substantial economic losses.

In the field of surface settlement prediction for shallow-buried tunnels, Peck proposed a classic empirical formula for estimating the volume of settlement trough based on the concept of ground loss using a large amount of measured data, which has become a commonly used method for surface settlement prediction in engineering [1].

O'Reilly supplemented through research on the settlement characteristics of clay and sand that the width coefficient of the settlement trough increases with the tunnel burial depth. In studies on special scenarios and model optimization, Saeid R proposed a Shallow Tunnel Classification System (STCS) based on the maximum settlement value, evaluating tunnel stability by integrating parameters such as burial depth and diameter [2,3]. She Fangtao et al. modified the traditional curve function for loess strata, improving the accuracy of longitudinal settlement description [4].

Xudong Wang et al. established a two-dimensional settlement propagation model based on the random medium theory, incorporating the randomness and inhomogeneity of soil layers to enhance prediction accuracy [5]. Dechun Lu et al. constructed a unified displacement function for circular tunnel sections, clarifying the law that vault settlement is greater than bottom rebound [6].

In terms of surrounding rock stability analysis, Cao Shiwei established a relational model including flatness ratio and bias pressure angle, revealing the correlation between tunnel failure modes and surrounding rock pressure [7]. Xie Jiajie proposed a surrounding rock stress calculation formula covering multiple factors such as ground load and support structure [8]. Regarding the application of numerical simulation technology, Guan Hongbing, Zhu Yongxiang et al. used FLAC 3D to simulate double-line shield tunnels, obtaining the laws of surface settlement curves [9]. Wang Jinhua conducted stochastic finite element analysis by combining ABAQUS and Matlab, verifying the consistency of settlement curve calculations [10].

Zhu Bin explored the disturbance characteristics of soil caused by overlapping tunnel construction using Midas software [11]. In field monitoring research, Yang Haiqin et al. confirmed the consistent downward trend of surface and vault settlement through comparison [12]. Cheng Zhengmin et al. obtained the excavation displacement laws of large-section variable-cross-section tunnels using the CRD method [13]. Miao Xueyun et al. acquired data on surface settlement, surrounding rock moisture content, and steel arch stress through testing components for tunnels in the loess tableland area [14].

Current research mostly focuses on ordinary shallow-buried tunnels, lacking special analysis for hub core area scenarios. Key construction issues such as the adaptive selection of excavation methods, the matching accuracy between numerical simulation parameters and hub strata, and the quantitative evaluation of "surrounding rock deformation, construction safety" still need in-depth exploration, which is difficult to fully meet the requirements of safe and efficient tunnel construction.

2. Project overview and construction simulation

2.1. Project overview

The research object is a shallow-buried concealed tunnel constructed by the bench cut method, with two main tunnels (left and right). Each tunnel has a net width of 18.5 m and a clear height of 5 m, with uniform structural dimensions to meet the engineering design load and traffic requirements. Before excavation, the outer contour of the tunnel and the middle internal bracing were poured in the soil using C40 concrete.

After pouring, taking the boundary between the silty clay layer and the coarse gravel layer as the dividing line, the upper and lower bench cut method was adopted for excavation, following the sequence: left half of the upper bench, left half of the lower bench, right half of the upper bench, and right half of the lower bench.

The exposed strata from top to bottom are Quaternary surface layer (fill soil, miscellaneous fill), alluvial-proluvial layer, eluvial-slope wash layer, and Carboniferous Shidengzi Formation bedrock, with significant differences in engineering mechanical properties among each layer.

2.2. Construction simulation

For the shallow-buried concealed section of the North Airport Tunnel, this study used GTS NX to establish a 2D model to simulate bench cut excavation.

Based on Saint-Venant's principle and the 18.5 m net width of the tunnel, the model was set to 100 m in length and 33.8 m in width. Since the distance from the tunnel top to the ground surface is only 6.25 m, the silty clay within 50 m on both sides of the central axis was reinforced by grouting with C20 concrete [15].

The Mohr-Coulomb model was applied to the soil layers, with parameters shown in the **Table 1** and **Figure 1** below.

Table 1. Mechanical parameters of each rock-soil layer and material

Rock-soil layer or material	Elastic modulus (kPa)	Poisson's ratio μ	Unit weight (kN/m³)	Cohesion C (MPa)	Internal friction angle φ (°)
Silty clay	50	0.3	15	22	11
Coarse gravel sand	100	0.3	16.5	5	20
Strongly weathered argillaceous siltstone	200	0.34	22	10	25
C20 grouted soil layer	500	0.2	22	10	23
C40	30	0.2	26	—	—

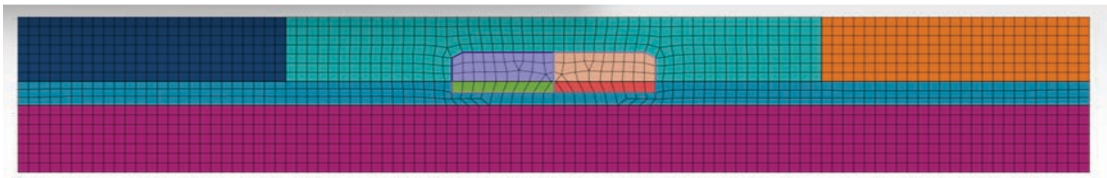

Figure 1. Tunnel construction model.

2.3. Analysis of simulation results

(1) Excavation of the left upper bench

It showed the characteristics of "upper settlement and lower heave". The maximum settlement above was 17.70 mm, the heave below was 7.53 mm, and the surface settlement was 12.6 mm. The settlement increased with the burial depth up to the tunnel top; only the left soil showed slight displacement.

(2) Excavation of the left lower bench

The deformation mode remained unchanged, but the displacement decreased. The maximum upper settlement was 16.38 mm, the lower heave was 5.76 mm, and the surface settlement was 11.3 mm.

(3) Excavation of the right upper bench

The "upper settlement and lower heave" pattern persisted. The upper settlement on the left was 14.59 mm and on the right was 13.6 mm; the lower heave on the right was 7.70 mm. The surface settlements on the left and right were 9.5 mm and 10.1 mm, respectively. The settlement increased with the burial depth up to the tunnel top, with only slight displacement on the right.

(4) Excavation of the right lower bench

The displacement further decreased. The top settlements on the left and right were 13.96 mm and 12.2 mm; the lower heaves were 5.2 mm and 4.9 mm; the displacements on both sides were 3.34 mm and 3.35 mm (basically symmetrical).

In summary, the entire excavation process was dominated by "upper settlement and lower heave", with displacement decreasing as excavation progressed. Surface settlement was significantly affected by shallow burial, while disturbances on both sides were small, verifying that the "support-first, excavation-later" approach is effective in controlling deformation.

3. Risk evaluation of surrounding rock stability in shallow-buried concealed tunnels based on FAHP

3.1. Determination of evaluation index weights

Following the core principle of the Analytic Hierarchy Process (AHP) – "focusing on dominant factors and ignoring secondary ones" – key control factors were extracted from numerous factors affecting tunnel excavation. Finally, a risk evaluation system for shallow-buried concealed tunnel construction was established, including 5 secondary indicators and 17 tertiary indicators.

Combined with actual conditions, comparisons were made between each index in the criterion layer and each factor within the criterion layer to obtain the judgment matrices of evaluation indicators for the criterion layer and the scheme layer. Weight vectors were calculated based on the judgment matrices at all levels, and consistency tests were conducted on the judgment matrices.

Judgment Matrix of Criterion Layer Evaluation Indicators

$$A_0 = \begin{pmatrix} 1 & 1/5 & 1/3 & 1/2 & 1/4 \\ 5 & 1 & 3 & 5 & 2 \\ 3 & 1/3 & 1 & 2 & 1/2 \\ 2 & 1/5 & 1/2 & 1 & 1/3 \\ 4 & 1/2 & 2 & 3 & 1 \end{pmatrix}$$

The maximum eigenvalue and the corresponding eigenvector that can be obtained through calculation

$$\lambda_{0\max} = 5.0682$$

$$a_0 = \left(0.1138, 0.8012, 0.2925, 0.1706, 0.4800\right)$$

The weight vector is obtained after normalization

$$\omega_0 = \left(0.0613, 0.4312, 0.1574, 0.0918, 0.2583\right)^T$$

$CI = 0.0170$, $RI = 1.12$, and $CR = 0.0152$ are calculated, so A meets the requirements, and this result can be used as the final decision weight.

Similarly, the consistency of the judgment matrices for the evaluation indicators in the scheme layer all meet the requirements. Based on the calculated weights of each factor, the excavation section size has the greatest impact, followed by vault settlement, while precipitation has the smallest impact, with the influence degrees of other factors falling in between.

3.2. Fuzzy-based construction safety risk analysis of shallow-buried concealed tunnels

To comprehensively evaluate the construction and excavation risks of shallow-buried concealed tunnels, this study refines several scheme layer indicators from multiple criterion layers (such as hydrogeological conditions and tunnel design conditions). It classifies the risk occurrence levels (e.g., "very likely", "likely") under each indicator and establishes the judgment matrix for the scheme layer.

The fuzzy synthesis operation for hydrogeological conditions is calculated as follows.

$$A_1 = \begin{pmatrix} 0 & 0.1 & 0.7 & 0.2 & 0 \\ 0 & 0.4 & 0.5 & 0.1 & 0 \\ 0 & 0.3 & 0.5 & 0.2 & 0 \\ 0 & 0.2 & 0.6 & 0.2 & 0 \end{pmatrix}$$

$$\omega_1 = \left(0.0721, 0.4761, 0.2471, 0.2047\right)$$

$$S_1 = \omega_1 \times A_1 = \left[0, 0.3127, 0.5349, 0.1524, 0\right]$$

Similarly, the fuzzy comprehensive evaluation for other criterion layers can be obtained. Then, a multi-level fuzzy comprehensive evaluation is conducted on them.

$$A = \begin{pmatrix} 0 & 0.3127 & 0.5349 & 0.1524 & 0 \\ 0 & 0.3763 & 0.5000 & 0.1172 & 0.0065 \\ 0 & 0.3526 & 0.4352 & 0.2000 & 0.0122 \\ 0 & 0.0742 & 0.6000 & 0.2000 & 0.1258 \\ 0 & 0.3649 & 0.5351 & 0.1000 & 0 \end{pmatrix}$$

$$\omega_0 = \left(0.0613, 0.4312, 0.1574, 0.0918, 0.2583\right)^T$$

$$S = \omega_0 \times A = \left[0, 0.3380, 0.5102, 0.1355, 0.0163\right]$$

The comprehensive evaluation result of the excavation risk of the shallow-buried concealed tunnel is obtained. This design adopts the principle of maximum membership degree, with the risk level value being 0.5102, corresponding to the risk evaluation result of "accidental".

4. Conclusion

To address the issue of risk management and control in the excavation of shallow-buried concealed tunnels, this study first identified key risk factors and constructed an evaluation system through literature research combined with engineering practice. Then, it established a risk evaluation system based on the Analytic Hierarchy Process (AHP), coupled with the fuzzy comprehensive evaluation method to quantify the risk level, and formed a control scheme.

The core results are as follows.

(1) Midas GTS NX simulation shows that after the excavation of this large-section tunnel, the top settlement and bottom heave are significant, and both decrease with the progress of excavation

(2) An evaluation index system including 5 criterion layers and 17 scheme layer factors was constructed. Weight calculation indicates that 5 factors such as excavation section size and vault settlement are core risk factors; after dividing the risk levels through fuzzy comprehensive evaluation, protective measures were proposed in combination with risk characteristics, providing support for construction safety.

Disclosure statement

The author declares no conflict of interest.

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Multi-Source Heterogeneous Data Fusion Analysis Platform for Thermal Power Plants

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Abstract: With the acceleration of intelligent transformation of energy system, the monitoring of equipment operation status and optimization of production process in thermal power plants face the challenge of multi-source heterogeneous data integration. In view of the heterogeneous characteristics of physical sensor data, including temperature, vibration and pressure that generated by boilers, steam turbines and other key equipment and real-time working condition data of SCADA system, this paper proposes a multi-source heterogeneous data fusion and analysis platform for thermal power plants based on edge computing and deep learning. By constructing a multi-level fusion architecture, the platform adopts dynamic weight allocation strategy and 5D digital twin model to realize the collaborative analysis of physical sensor data, simulation calculation results and expert knowledge. The data fusion module combines Kalman filter, wavelet transform and Bayesian estimation method to solve the problem of data time series alignment and dimension difference. Simulation results show that the data fusion accuracy can be improved to more than 98%, and the calculation delay can be controlled within 500 ms. The data analysis module integrates Dymola simulation model and AERMOD pollutant diffusion model, supports the cascade analysis of boiler combustion efficiency prediction and flue gas emission monitoring, system response time is less than 2 seconds, and data consistency verification accuracy reaches 99.5%.

Keyword: Thermal power plant; Multi-source heterogeneous data; Data fusion analysis platform; Edge computing

Online publication: Dec 10, 2025

1. Introduction

With the transformation of energy system to intelligent and efficient, thermal power plant, as the core infrastructure to ensure energy security, its equipment operation status monitoring and production process optimization has become the focus of the industry. In complex thermal cycle systems, the operation parameters, environmental data and operation and maintenance records of key equipment such as boiler, steam turbine and generator are heterogeneous from multiple sources. Traditional single-dimensional data analysis methods cannot meet the requirements of equipment life cycle management. By integrating data from physical sensors (temperature, vibration, pressure) with real-time operational data from SCADA systems, multi-source heterogeneous data fusion technology overcomes the limitations of single-source information, providing comprehensive decision support for equipment fault prediction and energy efficiency optimization [1]. For example, the fusion of infrared thermal imaging and 3d spatial data has been proven to have significant advantages in defect location and maintenance efficiency improvement in the monitoring of solar power plant equipment, and this cross-modal data integration strategy can also be applied to the state assessment of core equipment in thermal power plants.

2. Design of multi-source heterogeneous data fusion analysis platform for thermal power plants

2.1. Design of data fusion module

As the core component of the thermal power plant multi-source heterogeneous data fusion and analysis platform, the data fusion module should be designed to take into account the diversity of data collection, real-time processing and accuracy of analysis. This module establishes a multi-layered integrated architecture to enable deep interaction between physical and information spaces, ensuring effective integration of heterogeneous data from sensor networks, historical databases, and external systems. In the design process, based on the theoretical framework of data fusion, multi-dimensional data calibration and dynamic weight allocation strategy are adopted to solve the differences of different data sources in time series, format and dimension. In order to improve the data quality, the module introduces the abnormal detection algorithm based on physical constraints, and establishes the multi-parameter correlation model based on the operation mechanism of thermal power units, which can effectively eliminate the noise data and correct the measurement deviation.

In terms of implementation, the module first accesses various data sources through standardized interface protocols, including real-time sensor signals such as temperature, pressure and flow, as well as structured data from SCADA systems. To address the spatiotemporal alignment requirements of heterogeneous data, we employ time series interpolation and spatial coordinate mapping techniques to unify multi-source data under a unified spatiotemporal reference framework [2,3]. Subsequently, a 5D model based on digital twin technology establishes a mapping relationship between physical and virtual spaces. The physical model describes the unit's operational status, while the virtual model is updated in real-time through data fusion results, enabling bidirectional information flow interaction. This model integrates physical sensor data, simulation calculation results, and expert knowledge, forming a collaborative analysis foundation for multi-source information.

2.2. Data analysis and visualization module design

As the core function unit of the multi-source heterogeneous data fusion and analysis platform for thermal power plants, the data analysis and visualization module is mainly responsible for data processing, intelligent analysis and multi-dimensional visualization. The module is built on a B/S architecture, and the hierarchical design realizes the integration of the whole process of data collection, storage, calculation and display. The technical implementation fully integrates dynamic modeling, real-time communication and interactive visualization. At the data processing level, the module design includes data preprocessing, feature extraction and standardized transformation, which can effectively deal with the format difference and noise interference of multi-source heterogeneous data in the production process of thermal power plant. The system facilitates data exchange with underlying systems like DCS and SCADA through Web service interfaces, using XML for standardized data formats. By leveraging Ajax technology, it enhances real-time responsiveness on the client side, ensuring stable and timely data collection and transmission.

The data analysis module adopts a hybrid modeling strategy, which includes traditional methods such as statistical analysis and association mining, and integrates machine learning algorithms for complex pattern recognition. For example, to meet the dynamic monitoring requirements of key parameters such as boiler combustion efficiency and steam turbine vibration characteristics, the system introduced a simulation model developed on the Dymola platform.

Through comparison and verification with measured data, the system achieved high-precision prediction of equipment operating status. For multi-source data fusion analysis, the system adopts a cascaded modular architecture. Each data processing unit performs specific functions independently: the flue gas emission monitoring module integrates the AERMOD model for pollutant diffusion simulation, while the thermal system module achieves coordinated analysis of energy and material flows through a cascaded topology [4]. This modular design not only improves the scalability of the system, but also supports flexible configuration of the analysis process according to actual needs. For example, in the scenario of joint optimization scheduling, the system can call the wind power probability prediction model and thermal power load allocation algorithm to generate multi-objective optimization scheduling scheme.

3. Data collection and processing

3.1. Data collection methods

The data collection system design of the multi-source heterogeneous data fusion analysis platform for thermal power plants follows the principles of full life cycle coverage, multi-dimensional fusion and high real-time, and builds a distributed data acquisition architecture. The data sources of the platform include various heterogeneous data sources such as unit operation parameters, environmental monitoring data, equipment status information, production management records, and external meteorological energy data. The system implements a hierarchical data collection strategy tailored to different data sources. For time-series data requiring real-time processing, it establishes bidirectional communication interfaces with power plant DCS and SCADA systems via OPC UA protocol, enabling millisecond-level acquisition of critical parameters such as temperature, pressure, and flow rate from core equipment including boilers, steam turbines, and generators; For unstructured manual inspection records and equipment maintenance logs, structured processing is performed through customized data entry interfaces, utilizing natural language processing technology to extract key information fields. For third-party data sources such as environmental monitoring systems, standardized API interfaces and HTTPS encrypted transmission protocols are employed to ensure data integrity and security during collection.

In the data acquisition process, the system sets up a three-level quality assurance mechanism. First, the redundant sensors and intelligent gateway at the hardware layer realize the preliminary verification of the data source, and the adaptive filtering algorithm is used to eliminate the high-frequency noise interference. Secondly, the QoS Level 2 service quality is implemented at the transport layer using the MQTT protocol, ensuring transmission reliability through heartbeat packet detection and data packet retransmission mechanisms. Finally, a data preprocessing module is deployed on the edge computing node to perform timestamp synchronization, dimensionality unification, and format standardization on the collected raw data. For historical data requiring protocol conversion, the system employs ETL tools to transform industrial protocols such as Modbus, Profibus into standard JSON format, while establishing a data dictionary to map physical quantities to business semantics [5].

3.2. Data preprocessing and cleaning

In the process of data standardization and normalization, appropriate transformation strategies should be selected according to the distribution characteristics of different data types. For continuous variables, Z-score normalization is employed to eliminate dimensional differences, with the formula: where μ and σ represent the sample mean and standard deviation, respectively. Discrete variables are converted into numerical features through one-hot encoding. For text-based device status description data, a structured conversion process based on natural language processing is established to extract key semantic features through regular expressions and map them to a predefined classification coding system. In terms of data quality assessment, a multi-dimensional quality index system is constructed, including key indicators such as data integrity (missing rate < 0.5%), consistency (cross-system data deviation < 3%), timeliness (delay time < 10 seconds), etc., and the credibility of data is quantified by the quality scoring model [6]. To address format heterogeneity, ETL (Extract-Transform-Load) tools are employed to standardize data formats, including XML, CSV, and database tables. A metadata catalog is established to document source information such as data origin, collection time, and sensor model.

4. Experiment and analysis

4.1. Experimental methods and steps

This study takes the typical operation scenario of thermal power plant as the background, and adopts the multi-source heterogeneous data fusion analysis platform to carry out collaborative analysis of boiler combustion system, steam turbine power generation system and environmental monitoring system. The experiment design follows the whole process framework of "data collection, preprocessing, fusion modeling, verification and evaluation", and focuses on verifying the technical effectiveness of the platform in data space-time alignment, feature extraction and dynamic modeling.

The experimental data collection employed a hierarchical heterogeneous strategy. First, the SCADA system captured 32 types of time-series data (including boiler main steam temperature and pressure) with 1-second sampling intervals. Simultaneously, process parameters such as coal feed rate and air volume from the DCS system were sampled at 5-second intervals, while NOx emission concentration data from environmental monitoring stations were recorded every 10 minutes [7]. To ensure data integrity, a spatiotemporal reference coordinate system with multi-source data was established. All sensor devices were synchronized using GPS clocks, and data with different sampling frequencies were time-aligned through cubic spline interpolation. For unstructured data such as boiler endoscope video streams, the YOLOv5 model is employed to perform semantic segmentation of critical equipment components and extract flame morphology parameters.

4.2. Experimental results and analysis

In this experiment, a prototype system of multi-source heterogeneous data fusion analysis platform was constructed and tested in the actual operation environment of a 300MW thermal power unit, focusing on the performance of the platform in data integration efficiency, model prediction accuracy and system response performance. The experimental data included real-time sensor data from equipment such as boilers, steam turbines, and auxiliary systems, as well as historical operation records from SCADA systems, DCS control commands, and external meteorological data, with a total of about 2.5 million valid data samples collected. The cross-validation method is used to verify the performance of the fusion algorithm and compare the difference with the traditional single source data analysis method.

At the data fusion level, the platform employs ETL processes to convert data from multiple formats (including Modbus, OPC UA, and CSV) into standardized time-series sequences. The data cleansing module successfully identified and corrected 12.7% of outliers and missing data. In the feature engineering process, the sliding window method was used to extract time series features, and the fusion feature vector containing 42 dimensions was constructed by combining the statistics and frequency domain analysis. Experimental results show that after multi-source data fusion, the RMSE value of the boiler thermal efficiency prediction model decreased from 1.8% to 1.1% compared with single-source data, and the AUC value of steam turbine vibration prediction increased to 0.89, which is significantly better than the reference value of 0.76 of single sensor data [8].

5. Conclusion

In view of the urgent need for multi-source heterogeneous data fusion and analysis in thermal power plants, this study constructs an intelligent analysis platform based on edge computing and deep learning, whose core achievements are reflected in three aspects: technological system innovation, data processing capability improvement and engineering application value. By integrating data from SCADA systems, DCS control units, environmental monitoring devices, and IoT sensors, the platform has established a cross-level data fusion architecture for thermal cycles, combustion optimization, and equipment condition monitoring. This effectively resolves issues such as data silos, heterogeneous protocols, and insufficient real-time performance in traditional systems. At the data acquisition layer, a dynamic adaptation interface supporting OPC UA, Modbus TCP, MQTT and other protocols was developed to achieve millisecond-level collection and standardized conversion of key parameters of thermal power units (such as main steam temperature, boiler efficiency, pollutant emission concentration), with data integrity reaching more than 99.2%.

Disclosure statement

The authors declare no conflict of interest.

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Research on the Application of Digital Twin Technology in the Full Lifecycle Operation and Maintenance Management of Urban Road Infrastructure

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Abstract: With the continuous development of digital technology, urban management and urban construction have undergone tremendous changes, exerting a profound impact on people's lives. As a vital component of cities, urban road infrastructure is closely related to the daily lives of citizens. The application of digital twin technology can provide more support for the full lifecycle operation and maintenance management of urban road infrastructure, effectively improving the quality and efficiency of operation and maintenance management, ensuring the effectiveness of urban road infrastructure, and building a higher-quality urban life. Based on urban road infrastructure, this paper analyzes the application value of digital twin technology, proposes strategies for full lifecycle operation and maintenance management, and offers more references for urban construction.

Keywords: Digital twin technology; Urban roads; Infrastructure; Full lifecycle; Operation and maintenance management

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1. Introduction

The full lifecycle operation and maintenance management of urban road infrastructure is a comprehensive and complex management task that involves various stages, including planning, design, construction, operation, and maintenance of the infrastructure. With the accelerating process of urbanization, the demand for urban road infrastructure is also growing, highlighting the importance of its full lifecycle operation and maintenance management. Through the application of digital twin technology, real-time monitoring of the status and performance of urban road infrastructure can be achieved, enabling timely identification of issues and the implementation of targeted solutions. This promotes the construction of smart cities and provides citizens with more comfortable urban services.

1.1. Overview of digital twin technology

Digital twin technology is a product of the continuous development of digital technology. It creates corresponding virtual replicas for physical entities and uses them as platforms to effectively monitor the actual behavior and performance of these entities, thereby enabling analysis and evaluation. The concept of digital twins was first proposed by Michael Grieves in 2002 within the context of Product Lifecycle Management (PLM), and has since gradually been promoted and applied in fields such as aerospace and manufacturing [1,2]. Today, with the continuous development of artificial intelligence technology, the gradual popularization of Internet of Things technology, and the increasing maturity of big data technology, the application scope of digital twin technology has become increasingly widespread. It has become an indispensable tool for urban infrastructure management, providing more assistance to urban construction [3].

2. Application significance of digital twin technology

2.1. Improving the quality and efficiency of operation and maintenance management

Digital twin technology can provide managers with a 1:1 accurate model of urban road infrastructure, helping them more efficiently conduct performance tests on the infrastructure, design targeted operation and maintenance plans, reduce unscientific maintenance measures, ensure the efficient and high-quality operation of various infrastructure, and promote continuous improvement in the quality and efficiency of operation and maintenance management.

2.2. Ensuring the safety and reliability of operation and maintenance management

Digital twin technology can establish a real-time, dynamic monitoring system for urban road infrastructure. Through sensor networks deployed in structures such as roads, bridges, and tunnels, the system can continuously collect operational data such as deformation, stress, displacement, temperature, and humidity, and then conduct intelligent analysis and risk assessment of the operational status of the facilities. When abnormal fluctuations in monitoring data occur, the system can immediately generate warning signals, prompting managers to take targeted actions, thereby effectively reducing the probability of safety accidents.

Meanwhile, through the joint analysis of historical operational data and simulation models, the digital twin platform can identify high-risk areas and vulnerable components within the facilities, assisting management departments in formulating scientific inspection and maintenance plans. This data-driven dynamic monitoring mechanism not only enhances the real-time nature and accuracy of operations and maintenance but also provides reliable assurance for the long-term stable operation of urban infrastructure.

2.3. Achieving optimal allocation of operations and maintenance management resources

Digital twin technology can integrate with the actual conditions of urban road infrastructure operations and maintenance management to achieve optimal resource allocation, ensuring the quality of operations and maintenance management. This allows infrastructure to operate in its best possible state, providing greater assistance to urban residents in their travels. The system can scientifically allocate maintenance personnel, equipment, and financial investments based on the importance of facilities, operational loads, and risk levels, avoiding resource wastage and redundant operations. Additionally, the digital twin platform supports a quantitative evaluation mechanism based on ROI (Return on Investment), helping managers assess the input-output ratio of various operations and maintenance plans from an economic perspective and providing quantitative evidence for decision-making in urban infrastructure management. This data-driven refined management model not only improves the efficiency of operations and maintenance resource utilization but also promotes the sustainable development of the urban infrastructure operations and maintenance system [4].

3. Application of digital twin technology

3.1. Application in urban road infrastructure construction

3.1.1. Design phase

During the design phase of urban road infrastructure construction, digital twin technology can assist designers in optimizing design plans more conveniently [5]. Designers can use digital twin technology to create models of urban road infrastructure based on design requirements, analyzing potential climate conditions, usage requirements, and maintenance needs that the infrastructure may face in different virtual environments. By comparing the advantages and disadvantages of different design plans, designers can promptly identify issues and deficiencies in the design plans and take targeted measures for optimization. Through this virtual experimentation approach, design flaws can be identified in advance, construction rework can be minimized, construction costs can be reduced, and project timelines can be shortened [6].

Digital twin technology can also facilitate multidisciplinary collaboration in the design process of urban road infrastructure, enabling designers to complete scheme designs more efficiently. Urban road infrastructure is a comprehensive project that requires the joint participation of professionals from various fields, such as structural engineering and civil engineering. On the digital twin platform, engineers from different disciplines can enter the same virtual environment, enabling real-time information sharing and jointly driving continuous design optimization. This approach helps overcome information silos in traditional design models, further enhancing the feasibility of design schemes and promoting the continuous improvement of urban road infrastructure [7].

The design drawings completed through digital twin technology can also provide more comprehensive technical support for subsequent construction and operation and maintenance. During the design phase, designers need to consider the requirements for the operation and maintenance of urban road infrastructure throughout its entire lifecycle and incorporate potential maintenance issues into the design model. This approach allows for corresponding optimizations during the construction phase and facilitates the design of emergency response plans within the system, enabling timely access in case of unexpected issues and effectively mitigating severe consequences [8].

Additionally, operation and maintenance personnel can accurately understand the structure and function of various infrastructure components based on the system models uploaded by designers on the platform, thereby improving the quality and efficiency of infrastructure operations and ensuring that the overall performance of the infrastructure better meets the needs of different groups.

3.1.2. Construction phase

Digital twin technology enables real-time monitoring of the construction process of urban road infrastructure and simulates subsequent construction procedures through virtual simulation. This not only provides more precise guidance for construction but also significantly enhances construction efficiency and quality [9]. Construction personnel can also leverage digital twin technology platforms to simulate and analyze potential construction issues that may arise in the future, effectively predicting risks inherent in the construction process. This enables the formulation of more targeted strategies, ensuring the quality of urban road infrastructure construction and laying a solid foundation for subsequent operation and maintenance efforts.

Digital twin technology also facilitates the real-time collection of various types of data during the construction process and enables rapid sharing within the platform. Numerous sensors are often installed at construction sites, transmitting real-time construction data to the digital twin platform. Models are then constructed based on construction drawings and specific progress, allowing managers to visually observe the construction status of road infrastructure and evaluate construction effectiveness. This facilitates timely adjustments to construction plans in line with project deadlines and usage requirements [10].

Digital twin technology also provides construction personnel with a more convenient environment and conditions for equipment learning. On the platform, construction personnel can use virtual models to practice operating specific equipment, enabling them to better familiarize themselves with operational processes and related techniques while also mastering necessary emergency response measures. As a result, construction personnel can approach actual construction with confidence and promptly address unexpected situations, preventing any adverse impact on infrastructure projects [11].

Additionally, based on the construction needs of different infrastructure projects, digital twin technology can monitor the usage of various resources in real time, providing more comprehensive resource allocation plans in line with construction progress to ensure the efficient utilization of engineering resources. This not only significantly enhances construction quality and efficiency but also facilitates the operation and maintenance management of urban road infrastructure, effectively reducing cost consumption during the operation and maintenance process.

3.1.3. Operation and maintenance phase

Upon completion of construction, digital twin technology can conduct real-time analysis of the operational status of infrastructure, effectively monitoring the performance of various facilities and equipment. This can not only help operation and maintenance personnel more accurately grasp the basic structure and main functions of infrastructure, but also enable them to understand the service effectiveness of the infrastructure, so as to adopt more targeted strategies to design maintenance plans and effectively establish a virtuous cycle of operation and maintenance. Under this real-time monitoring mode, operation and maintenance personnel can not only detect abnormal phenomena in facilities and equipment, but also observe the status of these new facilities and equipment in the surrounding environment, so as to assess whether further environmental modifications and optimizations are required, thereby effectively reducing safety risks arising during the operation of infrastructure [12].

Digital twin technology can also predict the lifecycle of infrastructure. By combining relevant historical usage data and equipment performance reports, it can predict potential future failures through computational models and design more targeted maintenance plans, thereby supporting the extension of the service life of infrastructure.

3.2. Application in the maintenance and repair of urban road infrastructure

Maintenance and repair work is a crucial aspect of the entire lifecycle operation and maintenance of urban road infrastructure, largely determining its service effectiveness and lifespan. Therefore, through the application of digital twin technology, infrastructure can be maintained in a relatively good operational state, laying the foundation for improving urban service quality [13].

3.2.1. Preventive maintenance

Preventive maintenance is a key focus in infrastructure operation and management, requiring managers to regularly inspect the basic status of infrastructure during daily operations and take corresponding maintenance measures to ensure that equipment performance remains stable and good. The application of digital twin technology can further enhance the quality and efficiency of preventive maintenance. Building digital twin models on the platform enables effective monitoring of operational parameters for various infrastructure facilities, such as temperature, humidity, vibration, and so on. When abnormal values are detected, the system automatically sends alerts to management personnel and indicates the locations where the abnormal values have occurred, helping managers quickly locate and inspect them so that effective remedial measures can be taken.

Digital twin technology also enables managers to conduct in-depth analysis of historical data to explore the historical operational status of urban road infrastructure. For example, by combining historical maintenance records, managers can understand the main fault issues of the infrastructure and evaluate its overall operational performance through historical operational data. This approach allows for more precise identification of potential risks in the infrastructure and summarizes early characteristics of various faults, thereby facilitating more effective implementation of preventive maintenance and avoiding severe consequences caused by sudden failures [14].

Additionally, digital twin technology facilitates remote diagnosis and maintenance. Maintenance personnel can directly observe the actual state of the infrastructure through virtual models and perform remote operations via technical platforms. By leveraging the self-diagnostic capabilities provided by digital twin technology, they can more quickly locate faulty components in the infrastructure and complete repairs through remote guidance or operations, accelerating the restoration of infrastructure operations. This maintenance model not only reduces the time required for fault diagnosis but also lowers labor costs, enabling 24/7 uninterrupted monitoring of infrastructure. It ensures the normal operation of infrastructure and enhances urban service levels.

3.2.2. Emergency response

Emergency response is also a crucial aspect of the full lifecycle operation and maintenance of infrastructure, with digital twin technology further enhancing its efficiency. Digital twin models can directly provide managers with real-time parameters and status of infrastructure operations in the event of an emergency, helping them quickly grasp changes in the surrounding environment of the infrastructure, the functional status of its internal structure, and its operational conditions, among others. This enables managers to make rapid emergency decisions and formulate more efficient rescue and recovery plans.

Digital twin technology can also provide emergency response teams with different simulation scenarios to help them evaluate potential infrastructure failures and their consequences under various scenarios. This allows for the quickest possible response to rescue and fault handling in real-life scenarios that may arise in the future [15]. This not only significantly improves the reaction speed of emergency response teams but also ensures the accuracy of their emergency handling, effectively reducing losses and social impacts caused by emergencies. Additionally, digital twin technology can provide dynamically adjustable handling plans for emergency response teams based on the specific implementation of emergency responses, ensuring optimal allocation of resources and helping teams restore normal operation of various infrastructures more quickly.

Digital twin technology can not only provide emergency response teams with real-time captured on-site videos but also offer various precise data references through on-site sensors. It can also generate historical operation reports of infrastructure to help teams analyze the causes of infrastructure failures from different perspectives, more accurately determine maintenance considerations and potential risks, and provide scientific guidance for emergency actions. Furthermore, digital twin technology can provide remote command functions for emergency response services, allowing emergency personnel to further enhance the quality and efficiency of fault handling through remote guidance, providing more assistance in restoring road infrastructure to normal operation.

3.2.3. Performance optimization

Performance optimization is also an important aspect of the lifecycle management and operation of infrastructure, enabling managers to monitor the operational status and performance changes of infrastructure in real-time, thereby providing referenceable data for the optimization and upgrading of infrastructure. Digital twin technology can more accurately evaluate the energy efficiency and capacity of infrastructure, assess changes in it carrying capacity, and ensure its safe operation with normal parameters after upgrades and optimizations.

Meanwhile, managers can utilize digital twin technology to simulate the impacts of different upgrade and optimization plans on infrastructure and determine whether changes in maintenance plans affect the performance of infrastructure. This way, managers do not need to conduct multiple validations on the infrastructure through practical means, which not only saves optimization resources and time but also avoids causing damage to the infrastructure, providing a new approach for the upgrading and renovation of urban road infrastructure.

4. Challenges in the application of digital twin technology

Although digital twin technology demonstrates significant advantages in urban infrastructure management, its widespread adoption still faces multiple challenges. These issues are concentrated at the technical implementation and data governance levels, constraining the system's stability, scalability, and economic efficiency. To achieve sustainable development of digital twins, collaborative efforts are required in engineering practices, institutional design, and data ecosystem construction.

4.1. Technical implementation: Resource constraints in high-precision modeling and real-time simulation

Current city-level digital twin models often require the integration of multi-source heterogeneous data (geographic information, traffic flow, sensor data, etc.), resulting in high computational demands, long update cycles, and high operational costs. Particularly in high-precision 3D modeling and multi-physics field simulation, the return on investment (ROI) exhibits diminishing marginal returns, making it difficult to support long-term operations. Additionally, insufficient model standardization and interoperability of interfaces hinder the seamless integration of data and models across different departments, limiting the system's scalability.

4.2. Data governance: Institutional conflicts between privacy protection and data sharing

Digital twin systems rely on large-scale real-time data collection. However, in the context of smart cities, the widespread deployment of sensing devices involves public spaces and individual activity trajectories, which can easily lead to data security and privacy breaches. The existing data governance frameworks often prioritize security controls while overlooking the value of data reuse, exacerbating the phenomenon of "data silos". Additionally, the absence of unified data standards and evaluation systems results in inconsistent data quality, undermining the accuracy of model simulations and predictions.

4.3. Institutional and operational levels: Lagging standard systems and lack of management mechanisms

Urban-level digital twin projects generally lack top-level design guidance, with technical standards, evaluation indicators, and responsibility boundaries yet to be clearly defined. Some projects tend to prioritize construction over operation and maintenance, lacking sustained financial and talent support, which leads to a decline in system efficiency and delayed data updates in the later stages of operation.

Conclusion

In summary, during the entire lifecycle of operation and maintenance of urban road infrastructure, digital twin technology plays an increasingly vital role. It can effectively enhance the quality and efficiency of operation and maintenance, reduce costs and consumption, and assist managers in accurately locating faults, scientifically formulating plans, promptly responding to issues, and reasonably optimizing upgrades, thereby improving the operational performance of urban road infrastructure.

Disclosure statement

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Research on Technology and Risk Control Strategy in Real Estate Construction Engineering Management

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Abstract: The complexity of real estate construction project management is highlighted, and this paper deeply discusses its technology and risk control strategy. Analyze the application field of technology and the construction of risk management system, and verify the effectiveness of the strategy through cases. The is concluded that the integration of technology management and risk control is the core path to improve the efficiency of the project, and it points out that the application of intelligent tools should be strengthened and explore the new management mode under the dual-carbon goal.

Keywords: Real estate construction engineering management; Technology application; Risk control

Online publication: Dec 12, 2025

1. Introduction

Real estate construction project management, as the key to project success, is facing increasingly complex challenges. Against the backdrop of the current transformation and upgrading of the construction industry, traditional management models are no longer able to meet the demands of high-quality development. In October 2021, China issued the "Action Plan for Peaking Carbon Emissions Before 2030", which clearly requires the construction industry to promote green transformation, which puts higher demands on the technical application and risk control in real estate construction project management. Construction project management not only involves complex coordination in multiple stages, but is also influenced by various external factors such as market fluctuations and policy adjustments. On the technical level, the widespread application of emerging technologies such as prefabricated buildings and intelligent construction has improved construction efficiency and quality, but it has also put forward higher requirements for construction accuracy, process connection, and cross disciplinary collaboration. At the same time, the infiltration of green construction concepts requires the management process to take into account environmental benefits and form a multidimensional collaborative framework of "technology economy society". In this situation, in-depth research on the technology and risk control strategies in real estate construction project management, exploring their deep integration paths, is of great significance for improving project efficiency and achieving sustainable development of the industry.

1.1. Overview of real estate construction project management

1.1.1. Definition and core content of real estate construction project management

Real estate construction project management is the process of planning, organizing, coordinating, and controlling the entire life cycle of real estate projects using a systematic approach, covering stages such as project planning, design, construction, delivery, and operation and maintenance, with the aim of achieving a balance between quality, cost, schedule, and safety goals. Its core content includes resource integration and configuration optimization, scientific decision-making of technical solutions, risk identification and dynamic control, as well as the construction of a multi-party collaboration mechanism. Modern engineering management emphasizes the full process digital empowerment, such as the application of BIM technology to achieve integrated design and construction, and the integration of prefabricated building technology to promote standardization and industrialization. At the same time, the infiltration of green construction concepts requires consideration of environmental benefits in the management process, forming a multidimensional collaborative framework of "technology economy society". On the theoretical level, it relies on systems engineering theory, project management methodology, and lean construction thinking, while on the practical level, it needs to combine policy norms, market dynamics, and technological innovation to form a dynamic adaptive management system.

1.2. The main challenges of current real estate engineering management

Real estate engineering management faces multiple complex challenges. The problems of project schedule pressure and cost overruns are prominent, influenced by market fluctuations, policy regulation, and unstable supply chain factors. The phenomenon of project cycle compression and budget loss control is frequent, and material price fluctuations, frequent design changes, and labor shortages further exacerbate cost risks. The technological complexity has significantly increased, and the application of emerging technologies such as prefabricated buildings and intelligent construction has put forward higher requirements for construction accuracy, process connection, and cross disciplinary collaboration. Traditional management models are difficult to adapt to modular construction and digital driven technological iteration. The difficulty in resource coordination manifests as conflicting goals among multiple stakeholders, such as unclear division of responsibilities between developers, contractors, design units, and government departments, and information gaps across stages leading to decision-making delays [1]. In addition, the tightening of environmental regulations and the requirements for energy conservation and emission reduction under the "dual carbon" target have forced engineering management to incorporate sustainability considerations in the selection of technical paths and resource allocation, further increasing management complexity. It is urgent to build a resilient management system through technological innovation and institutional optimization to cope with uncertainty in dynamic environments [2].

2. Key areas of real estate construction engineering technology management

2.1. Application and management of prefabricated building technology

Prefabricated building technology focuses on standardized design, factory production, and modular construction, and achieves innovation in engineering construction mode through efficient integration of prefabricated components. Its core advantage lies in standardized production, which reduces the amount of on-site work, shortens the construction period, and reduces manual dependence. At the same time, its green features are significant, responding to the demand for sustainable development by reducing construction waste and energy consumption. However, prefabricated construction faces technical difficulties, and the reliability of node connections and overall structural stability rely on refined processes. For example, the precision control of grouting sleeve connections and bolt anchoring directly affects building safety; The coordination requirements between component production and on-site installation are strict, and dimensional deviations can easily lead to assembly failures. Therefore, 3D scanning and BIM technology are needed to assist in error correction [3]. In addition, insufficient supply chain management and cross stage collaboration may exacerbate technical risks, and a full chain quality control system needs to be established to ensure the implementation of technology.

2.2. Engineering management driven by digital technology

Digital technology has reconstructed the traditional engineering management model, and BIM technology integrates design, construction, and operation data through 3D models to achieve cross disciplinary collaborative design and conflict detection, optimize construction plans, and reduce rework [4]. BIM based 4D/5D simulation during the construction phase can accurately predict progress and costs, improving resource scheduling efficiency. The Internet of Things and intelligent monitoring system collect real-time data on the construction site environment, equipment status, and personnel behavior through sensors, and combine AI algorithms to analyze safety hazards and quality defects, dynamically adjusting management strategies. For example, the tower crane operation monitoring and deep foundation pit deformation warning system can reduce the risk of accidents, and RFID technology can achieve accurate management of building materials traceability and inventory. The deep application of digital technology relies on data standardization and system compatibility, requiring the construction of a unified platform to break information silos and promote the transformation of engineering management towards intelligence and transparency.

3. Construction of risk management system for real estate engineering

3.1. Identification and assessment of engineering risks

3.1.1. Classification of main risk factors

Real estate engineering risks can be divided into two categories: technical risks and non-technical risks. Technical risks arise from technical defects in the design and construction process, such as building functional conflicts caused by lagging design specifications, structural safety hazards caused by immature connection processes of prefabricated component nodes, or quality deviations caused by insufficient adaptability of construction technology. Non-technical risks involve uncertainty in the external environment, including the impact of policy adjustments on project compliance (such as changes in land transfer rules, upgrades to environmental standards), delays in building material supply or cost surges caused by supply chain disruptions, and the risk of funding chain disruptions caused by market fluctuations. Two types of risks interact with each other, for example, policy tightening may force technological path adjustments, while insufficient technological iteration may amplify policy compliance risks [5]. It is necessary to construct a multidimensional risk list through a systematic identification framework, combined with the characteristics of the entire project cycle, to provide a basis for subsequent evaluation and control.

3.1.2. Risk assessment methods

The Analytic Hierarchy Process (AHP) quantifies the weight and priority of risk factors by constructing a hierarchical structure model of “objectives criteria indicators”, which is suitable for complex risk assessment scenarios with multiple objectives and multiple subjects. For example, breaking down technical risks into sub items such as design, construction, and materials, and combining expert scoring to determine the relative importance of each level. The risk matrix rule divides risk events into “high medium low” levels through probability impact two-dimensional analysis, achieving the transformation from qualitative to quantitative. The combination of the two can improve evaluation accuracy: AHP solves the problem of indicator weight allocation, and the risk matrix clarifies the ranking of risk levels [6]. In practice, it is necessary to dynamically update evaluation parameters, such as policy change frequency and supply chain stability data, and use Monte Carlo simulation to predict risk superposition effects, in order to enhance the timeliness and reliability of evaluation results.

3.2. Risk management strategy

3.2.1. Organizational measures

The allocation of risk responsibility should be based on contract terms and stakeholder roles, clarifying the risk bearing boundaries of developers, general contractors, design institutes, and supervisors, such as transferring technical risks to contractors through the EPC general contracting model. The emergency plan system should include risk warning thresholds, response processes, and resource reserves, such as setting up emergency special funds to deal with supply chain disruptions, or establishing a policy tracking team to interpret regulatory changes in real time. In terms of organizational collaboration mechanism, regular joint meetings and information sharing platforms should be held to ensure risk linkage response among design, construction, procurement and other departments, and to avoid risk diffusion caused by information silos.

3.2.2. Technical measures

Redundancy design enhances the system's ability to resist risks by increasing structural safety factors or backup supply chain paths, such as reserving adjustment margins for components in prefabricated buildings to cope with installation errors. Dynamic monitoring technology relies on sensors, BIM, and IoT platforms to collect real-time construction data and analyze anomalies, such as warning of prefabricated node deformation through stress monitoring, or simulating design compliance after policy changes using BIM models [7]. Technical measures need to be deeply integrated with digital tools, such as embedding risk matrices into BIM systems to automatically trigger warnings, or using machine learning algorithms to predict the probability of supply chain disruptions, to achieve a transition from passive response to active intervention, forming a closed-loop management chain of "monitoring analysis decision-making feedback".

4. Technology and risk collaborative control strategy

4.1. Collaborative mechanism between technical management and risk control

4.1.1. Integration of technical standards and risk management processes

The synergy between technical standards and risk management processes needs to be embedded in the PDCA (Plan Do Check Act) cycle framework, forming a closed-loop optimization mechanism. During the planning phase, technical standards are used to clarify design specifications and construction processes, and a risk identification checklist is developed simultaneously; Real time monitoring of construction quality and risk trigger points during the execution phase, combined with BIM and IoT technology, such as automatic warning when the installation deviation of prefabricated components exceeds the limit; During the inspection phase, digital tools are used to compare actual data with technical standards, analyze the root causes of deviations, and assess the impact of risks; Dynamically adjust technical solutions and control strategies during the processing phase, such as optimizing node connection processes or updating emergency plans. This model achieves a bidirectional coupling of "technical compliance risk controllability" through rigid constraints of technical standards and flexible adaptation of risk management, reducing secondary risks caused by technical defects [8].

4.1.2. Cross departmental collaboration and information sharing mechanism

Cross departmental collaboration requires building a collaborative network centered around data flow, breaking down information barriers between design, construction, procurement, and operations departments. For example, a collaborative platform based on BIM integrates design drawings, material lists, and construction progress data to ensure real-time transmission of risk information between departments. The information sharing mechanism relies on standardized data interfaces and permission allocation, such as synchronously pushing supply chain interruption risk warning signals to the procurement and project departments to trigger joint decision-making. Through regular risk joint meetings and digital dashboards, clarify the responsibility boundaries and response time of all parties, and avoid risk escalation caused by communication lag. In addition, blockchain technology can enhance data credibility, record the entire process of risk event handling, and provide a basis for responsibility tracing and experience reuse.

4.2. Dynamic control supported by information platform

4.2.1. Construction of BIM + risk warning system

The integration of BIM and risk warning system advances risk control to the design stage, with a risk parameter library embedded in the model (such as policy compliance indicators, structural safety thresholds), automatically detecting design conflicts and construction feasibility risks. During the construction phase, BIM models are linked with sensor data to map real-time on-site progress and quality status, such as monitoring the installation accuracy of prefabricated components, triggering warnings and pushing correction plans when exceeding limits. The system supports risk visualization display, identifying risk levels through red, yellow, and green colors to assist managers in quickly identifying high priority issues. This model breaks through the limitations of traditional static control and forms an intelligent control chain of “model driven data feedback dynamic adjustment”.

4.2.2. Risk prediction and decision-making driven by big data

Big data technology integrates historical project data, market dynamics, and policy texts to construct multidimensional risk prediction models. Machine learning algorithms analyze the correlation patterns of supply chain interruptions, project delays, and other events, quantifying the probability and scope of risk occurrence. For example, predicting cost overruns risk based on time-series data of building material price fluctuations, or using natural language processing technology to capture policy keywords and predict compliance risk trends. The decision support system integrates predicted results with real-time data to generate multi scenario response plans, such as dynamically adjusting procurement plans or optimizing construction processes. The data-driven decision-making model reduces subjective judgment bias, enhances the foresight and accuracy of risk response, and promotes the transformation of engineering management from experience oriented to science oriented.

4.3. Typical case analysis

4.3.1. Technical risk management practice for prefabricated residential projects

Prefabricated residential projects need to focus on the synergy between component production, transportation, and installation in technical risk management. Taking the Gucun Town resettlement housing project in Baoshan District, Shanghai as an example, it adopts a standardized design with a prefabrication rate of 36.1%, using prefabricated exterior wall panels, composite floor slabs and other components, but faces the risks of component size deviation and node connection hazards.

The project uses 3D laser scanning technology to detect the accuracy of prefabricated components, combined with BIM models for error correction to ensure installation compatibility; At the same time, establish a full chain quality control system, implement “one component, one file” traceability management from factory production to on-site lifting, and reduce the rate of component damage. To address the risk of node connection, a composite process of grouting sleeve and bolt anchoring is adopted, and real-time monitoring of node stress changes is carried out through IoT sensors. The data is integrated into the BIM platform to generate risk warning reports and achieve dynamic control [9].

In addition, the project introduces PDCA cycle optimization process standards, such as adjusting the grouting material ratio through post construction evaluation to improve node reliability. This case demonstrates that technology risk management needs to integrate digital tools and lean management, and strengthen full process collaboration.

4.3.2. Full cycle risk management of high-rise building complex projects

High rise building complex projects require the establishment of a risk management system that covers the entire lifecycle due to their complex functions and numerous participants. Taking a commercial complex project in the core area of a certain city as an example, its integrated risk identification, assessment, and response mechanism runs through the design, construction, and operation stages. During the design phase, BIM technology is used to simulate building functional conflicts and structural safety, and identify potential design defects; During the construction phase, the Internet of Things system is used to monitor the deformation of deep foundation pits and the operation status of tower cranes, combined with a risk matrix to quantify safety risk levels and trigger graded response plans.

To address the risk of supply chain disruptions, establish a diversified supplier database and safety stock mechanism, and record contract performance data through blockchain technology to reduce the probability of default. During the operation and maintenance phase, we rely on big data platforms to analyze historical data on energy consumption and equipment failures, and predict maintenance needs. The project also integrates data from the design institute, general contractor, and supervisory party through a cross departmental information sharing platform to achieve risk linkage response, such as quickly adjusting fire compliance design when policies change. The full cycle risk management model deeply integrates technical measures (such as redundant structure design) with organizational measures (such as joint meeting system), effectively enhancing project resilience [10].

5. Summary

In the management of real estate construction projects, the deep integration of technology and risk control is the core path to improve project efficiency. This article systematically expounds the connotation and challenges of real estate construction project management, deeply analyzes the application and management points of key technology fields such as prefabricated building technology and digital technology, and constructs a comprehensive risk management system covering risk identification, evaluation, and control strategies.

At the same time, it explores the dynamic control mode supported by technology and risk collaborative control mechanism and information platform, and verifies the effectiveness of the proposed strategies through typical case analysis. Research has found that the coordinated promotion of technology management and risk control can not only effectively address the complex challenges in current real estate engineering management, but also significantly improve the achievement of project quality, cost, schedule, and safety goals.

However, there are still shortcomings in current research, and the deep application of intelligent tools in risk prediction needs to be strengthened. The new management mode under the dual carbon target needs further exploration. Future research will focus on the integration and innovation of intelligent technology, in order to provide more accurate and efficient risk prediction and control solutions for real estate construction project management, and promote the industry’s development towards green, intelligent, and resilient directions.

Disclosure statement

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Research on the Control of Construction Period Risks by BIM Modeling Optimization in the Pre-construction Stage of Industrial Factory Buildings

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Abstract: This research focuses on using BIM modeling optimization to control construction - period risks in the pre-construction stage of industrial factory buildings. It analyzes common risk factors and limitations of traditional approaches. BIM-based methods like collision detection, 4D simulation, multi-dimensional data integration, etc., can effectively mitigate risks. Stakeholder collaboration, digital twin testing, and lean BIM integration is also crucial. Case studies show BIM can reduce risks by 32–41%, with a three phase roadmap provided.

Keywords: BIM modeling optimization; Construction period risk; Industrial factory building

Online publication: Dec 12, 2025

1. Introduction

In recent years, with the global emphasis on industrial development, policies like the "New Industrial Construction Promotion Plan" (issued in 2024) aim to boost the efficiency and quality of industrial factory building construction. In the pre-construction stage of industrial factory buildings, controlling construction period risks is vital for project success and economic benefits. Traditional risk control methods face limitations, while Building Information Modeling (BIM) has emerged as a powerful solution. Prior studies have also confirmed the advantages of BIM in enhancing risk management and improving project performance in construction projects [1]. This paper explores the specific application and effectiveness of BIM modeling optimization in managing construction period risks, including collision detection, 4D simulation, multidimensional data integration, and more, to ensure high quality and on time project completion in line with the spirit of the new policy.

2. Construction period risk analysis in industrial factory projects

2.1. Common risk factors in industrial construction

2.1.1. Construction period risk analysis in industrial factory projects

In industrial factory projects, several common risk factors can impact the construction period. Design conflicts are prevalent. The complexity of industrial factory designs, involving multiple systems such as production lines, ventilation, and electrical systems, often leads to clashes between different design elements. For example, the layout of equipment might conflict with the planned routing of pipes or cables. These conflicts usually surface during construction, causing rework, extended construction time, and increased costs [2].

Material logistics delays are another significant risk. Industrial construction requires a large quantity of specialized materials. Unforeseen circumstances in the supply chain, like supplier bankruptcies, transportation disruptions due to natural disasters or geopolitical issues, can cause shortages. If materials do not arrive on site as scheduled, construction activities will be halted, inevitably delaying the project timeline.

Process coordination failures also pose a threat to the construction period. Industrial construction involves various trades, including civil engineering, mechanical, and electrical installation. Poor communication and lack of effective coordination among these different teams can result in sequential or concurrent work not being carried out in an orderly manner. For instance, if the electrical team starts wiring before the civil work for wall partitions is completed, it may lead to inefficiencies, rework, and ultimately, delays in the overall construction schedule.

2.2. Limitations of conventional risk prevention approaches

2.2.1. Construction period risk analysis in industrial factory projects

Traditional 2D drawing validation and manual scheduling methods in industrial factory projects have significant limitations. In terms of 2D drawing validation, the flat nature of 2D drawings fails to provide a comprehensive and intuitive view of the project. It is difficult to detect potential spatial conflicts, such as clashes between different building components, in a timely manner. This often leads to rework during construction, thus delaying the project schedule [3]. For example, in some delayed industrial projects, hidden problems like pipe collisions in the building's interior were not discovered until construction began, which required the readjustment of pipeline routes, consuming additional time and resources.

Manual scheduling, on the other hand, is highly labor intensive and prone to human errors. Schedulers need to consider numerous factors, including resource allocation, task dependencies, and construction sequences. As the complexity of industrial factory projects increases, it becomes extremely challenging to accurately balance these elements. Moreover, manual scheduling lacks real time adaptability. When unexpected events occur, such as bad weather or material shortages, it is difficult to quickly adjust the schedule to minimize the impact on the construction period. These limitations of conventional approaches highlight the urgent need for more advanced methods, like BIM based modeling optimization, to better control construction period risks in industrial factory projects.

3. BIM modeling optimization for risk mitigation

3.1. BIM-based collision detection and design validation

3.1.1. BIM-based collision detection and design validation

In the pre-construction stage of industrial factory buildings, BIM tools play a crucial role in detecting collisions and validating designs, thus mitigating construction period risks. For complex industrial MEP (Mechanical, Electrical, and Plumbing) systems, BIM technology enables automatic clash detection. This is highly beneficial as it can identify potential conflicts between different building components, such as pipes, ducts, and electrical conduits, which might not be easily spotted through traditional 2D drawings. For example, in the energy plant layout within the industrial factory building, BIM can precisely analyze the spatial relationships among various equipment, pipes, and power related facilities.

By using BIM for spatial validation, designers can ensure that the proposed design meets the functional and spatial requirements. It helps to verify if there is sufficient space for equipment installation, maintenance, and operation. In the case of the energy plant layout optimization, spatial validation via BIM can determine whether the planned arrangement of energy - related equipment allows for easy access for inspection and repair, without compromising on safety and efficiency. This not only reduces the likelihood of design errors but also minimizes the need for rework during construction. Rework often leads to delays and increased costs, which are significant construction period risks. Through BIM based collision detection and design validation, these risks can be effectively mitigated, ensuring a smoother construction process for industrial factory buildings [4].

3.2. 4D construction simulation and schedule optimization

3.2.1. 4D construction simulation and schedule optimization

The conversion of 3D BIM models into 4D construction simulations is a crucial approach in controlling construction period risks in the pre-construction stage of industrial factory buildings. By integrating the element of time into the 3D BIM model, a 4D simulation can be created, which provides a dynamic view of the construction process.

In factory projects, this 4D simulation is used to analyze crew flow optimization. It allows project managers to visualize how different construction teams move around the site at various times. For example, in a large scale factory construction, the movement of the foundation - laying crew, the steel structure installation crew, and the interior finishing crew can be precisely simulated. This helps in identifying potential bottlenecks in crew movement, such as overcrowded work areas at certain time points. By optimizing crew flow, the overall construction efficiency can be improved, reducing the likelihood of delays caused by crew related issues.

Regarding prefabrication scheduling, the 4D simulation plays a vital role as well. Factory buildings often involve a significant number of prefabricated components. The 4D model can accurately schedule the production, transportation, and installation of these prefabricated elements. It ensures that prefabricated parts are ready at the right time for installation on site, avoiding waiting times that could extend the construction period. For instance, if a prefabricated wall panel is scheduled to be installed on a specific day, the 4D model can track its production progress in the factory, its transportation route, and ensure it arrives on site just in time. Overall, through 4D construction simulation and schedule optimization, construction period risks can be effectively mitigated in industrial factory building projects [5].

4. BIM-driven risk control framework development

4.1. Risk early warning system architecture

4.1.1. Multi-dimensional data integration framework

A multi-dimensional data integration framework is crucial for the risk early - warning system in the BIM driven risk control framework. This framework proposes a data integration structure that combines BIM models, ERP schedules, and IoT sensor inputs [6].

BIM models, as the core of this integration, contain rich geometric and semantic information about the industrial factory building. They provide a three dimensional visual representation of the project, enabling stakeholders to clearly understand the building's structure and components. ERP schedules, on the other hand, are designed to manage and optimize the project's time related aspects. By integrating ERP schedules with BIM models, it becomes possible to align the construction progress in terms of time with the physical construction represented by the BIM models. This helps in predicting potential schedule related risks such as delays.

IoT sensor inputs add a real time and dynamic dimension to the data integration. These sensors can be installed at various construction sites to collect data on factors like temperature, humidity, equipment operation status, and worker location. When integrated with BIM models and ERP schedules, this real time data allows for immediate identification of risks. For example, if an IoT sensor detects abnormal equipment operation, it can be correlated with the BIM model to locate the equipment in the building and with the ERP schedule to understand how this might impact the overall construction period. Through this multi-dimensional data integration framework, a comprehensive and real time risk monitoring system can be established, enhancing the ability to control construction period risks in the pre-construction stage of industrial factory buildings.

4.1.2. Risk quantification algorithms

Risk Quantification Algorithms play a crucial role in the BIM Driven Risk Control Framework for construction period risks in the pre-construction stage of industrial factory buildings. Based on BIM derived construction process parameters, mathematic models are developed to quantify schedule deviation risks [7]. These algorithms take into account various factors such as the duration of each construction activity, the sequence of tasks, and resource allocation data obtained from BIM models. For example, by analyzing the start and end times of different construction operations in the BIM simulated construction process, the algorithms can calculate the potential deviation of the overall project schedule. They also consider the dependencies between tasks, like which activities must be completed before others can start. The algorithms use statistical and analytical methods to translate these BIM based parameters into numerical risk values. This enables project managers to have a clear understanding of the level of risk associated with schedule deviations. For instance, a high numerical risk value indicates a significant potential for schedule delay, while a low value implies relatively stable schedule conditions. Through these algorithms, the risk quantification process becomes more accurate and objective, providing a solid foundation for effective risk control and decision making in the pre-construction stage of industrial factory buildings.

4.2. Implementation workflow for pre-construction optimization

4.2.1. Stakeholder collaboration protocol

To ensure the successful implementation of the BIM driven risk control framework in the pre-construction optimization of industrial factory buildings, a well-defined stakeholder collaboration protocol is essential. The protocol aims to integrate design, construction, and supplier teams for concurrent engineering optimization.

Design teams play a fundamental role. They are responsible for creating accurate and detailed BIM models that incorporate all aspects of the factory building design, from architectural layouts to structural and MEP (mechanical, electrical, and plumbing) systems. These models serve as the basis for risk identification and mitigation discussions among stakeholders.

Construction teams bring their onsite experience to the table. They can identify potential construction related risks during the pre-construction stage, such as accessibility issues, construction sequencing challenges, and safety hazards. By collaborating with the design team through the BIM platform, they can propose design modifications to eliminate or reduce these risks.

Supplier teams are also crucial. They provide information regarding the availability, delivery schedules, and compatibility of building materials and equipment. This information is integrated into the BIM model, enabling the entire project team to anticipate supply–chain–related risks. For example, long lead items can be identified early, and alternative sourcing strategies can be developed [8].

Regular communication channels, such as BIM based meetings and shared digital platforms, should be established among these stakeholders. This allows for real time information sharing, efficient decision-making, and seamless coordination, which are vital for effective risk control in the pre-construction optimization of industrial factory buildings.

4.2.2. Digital twin-based scenario testing

Digital Twin-Based Scenario Testing in the implementation workflow for pre-construction optimization is of great significance. A digital twin, a virtual replica of the physical construction project, is created, which mirrors every aspect of the industrial factory building's pre-construction stage [9]. This digital twin enables the evaluation of various construction scenarios. For example, different construction sequences can be virtually simulated. By inputting the relevant data of different construction orders into the digital twin model, the potential impacts on the construction period can be observed. If one sequence involves overlapping tasks that could lead to resource contention, the digital twin will display the resulting delays. Resource allocation strategies can also be tested. Suppose there are limited construction machinery and labor resources. The digital twin can model different allocation plans, such as distributing more resources to the foundation work first or focusing on the superstructure construction initially. Through these simulations, the project team can understand which strategy can minimize construction period risks.

Moreover, the digital twin can integrate real - time data from sensors during the pre-construction stage, making the scenario testing more accurate and dynamic. This helps in making well - informed decisions to optimize the pre-construction process and control construction period risks effectively.

5. BIM-integrated project management process improvement

5.1. Process re-engineering for model-centric delivery

5.1.1. Lean construction–BIM integration

The Lean Construction–BIM Integration combines the principles of lean construction with BIM technology to enhance the efficiency and effectiveness of construction projects. Lean construction emphasizes minimizing waste, improving value flow, and promoting continuous improvement in construction processes. BIM, on the other hand, provides a digital platform for integrated design, construction, and management.

By integrating these two, construction teams can use BIM derived construction workflow analytics to redesign value stream mapping processes. This integration helps in visualizing the entire construction process, identifying bottlenecks, and eliminating non value added activities. For example, BIM models can accurately represent the sequence of construction operations, allowing lean principles to be applied more precisely. It enables better resource allocation, as construction managers can see in real time how different tasks interact and how resources are utilized [10].

Moreover, the combination of lean construction and BIM promotes a collaborative environment. All stakeholders, including architects, engineers, contractors, and suppliers, can work together more effectively, sharing information and making decisions based on the integrated BIM model. This reduces rework, improves communication, and ultimately leads to better control of construction period risks in the pre-construction stage of industrial factory buildings. Overall, Lean Construction–BIM Integration is a powerful approach to optimize construction processes and achieve more efficient project delivery.

5.1.2. Automated change order management

Automated Change Order Management is a crucial aspect within the framework of BIM–Integrated Project Management Process Improvement for model centric delivery. By implementing a model based change impact analysis system, the process of rapid design modification approvals can be significantly enhanced.

This system uses the BIM model as the core. When a change order occurs, the model can quickly analyze the potential impacts on various aspects of the project, such as construction schedule, cost, and building performance. For example, if there is a proposed change in the layout of an industrial factory building, the system can immediately calculate how this change will affect the installation of equipment, the movement of construction materials, and the overall construction sequence.

The automated nature of this system reduces manual errors and speeds up the decision making process. It provides project managers, designers, and stakeholders with accurate and timely information about the implications of design modifications. This enables them to make more informed decisions regarding whether to approve or reject a change order. In the pre-construction stage of industrial factory buildings, where time is of the essence, this kind of efficient change order management based on BIM can effectively control construction period risks. By quickly assessing the impacts of changes and making prompt decisions, potential delays caused by design changes can be minimized, ensuring the project progresses smoothly as planned [11].

5.2. Collaborative decision-making mechanisms

5.2.1. Cloud-based model sharing platform

The cloud-based model sharing platform plays a crucial role in the BIM–integrated project management process improvement, especially in facilitating collaborative decision making mechanisms. This platform serves as a central repository where all project-related BIM models can be stored, shared, and accessed by different stakeholders, including architects, engineers, contractors, and facility managers [12].

With this platform, real time access to the most updated BIM models is ensured. Stakeholders can review the models from anywhere with an internet connection, which breaks down the geographical and temporal barriers. For example, an architect in one city can collaborate with an engineer in another country on the same BIM model simultaneously. This real time sharing enables quick identification of potential issues during the pre-construction stage of industrial factory buildings.

Moreover, the cloud-based model sharing platform supports version control. Every change made to the BIM model is tracked, and previous versions can be retrieved if necessary. This feature is vital for maintaining the integrity of the design process and for auditing purposes. It also allows stakeholders to understand the evolution of the design, which is beneficial for making informed decisions.

In addition, the platform can integrate with other project management tools. For instance, it can be linked to scheduling software, so that any changes in the BIM model can be automatically reflected in the project schedule. This seamless integration further enhances the efficiency of the collaborative decision making process, helping to better control the construction period risks in the pre-construction stage of industrial factory buildings.

5.2.2. Risk-based schedule optimization algorithms

Risk-Based Schedule Optimization Algorithms integrate Monte Carlo simulations with BIM schedules to achieve probabilistic timeline forecasting. The Monte Carlo method is a powerful computational algorithm that can handle uncertainties effectively. By running a large number of simulations, it can generate a range of possible outcomes for the project schedule, taking into account various risk factors. When combined with BIM schedules, this approach provides a more comprehensive view of the project timeline.

BIM schedules contain detailed information about tasks, dependencies, and resource allocation. Integrating Monte Carlo simulations into BIM schedules allows project managers to assess the probability of different schedule scenarios. For example, they can determine the likelihood of meeting a specific deadline or identify the tasks that pose the highest risk to the schedule. This probabilistic timeline forecasting enables more informed decision making. Instead of relying on deterministic estimates, project teams can base their strategies on a better understanding of the potential variability in the schedule. With this risk based approach, they can prioritize risk mitigation efforts, allocate resources more effectively, and develop contingency plans. Overall, the integration of Monte Carlo simulations and BIM schedules through risk based schedule optimization algorithms significantly enhance the control of construction period risks in the pre-construction stage of industrial factory buildings [13].

5.3. Performance monitoring and continuous improvement

5.3.1. Key risk indicator tracking system

Implementing a dashboard to monitor BIM predicted versus actual construction progress metrics is a crucial step in the Key Risk Indicator Tracking System. This dashboard serves as a visual hub that enables project managers and stakeholders to quickly identify discrepancies between what was predicted using BIM technology and what is actually occurring onsite during the construction of industrial factory buildings.

By constantly comparing these metrics, trends can be detected early. For example, if the BIM predicted rate of foundation construction is faster than the actual rate, it could be an indication of potential risks such as equipment breakdowns, labor shortages, or unforeseen soil conditions. These early detections allow for proactive risk management.

The Key Risk Indicator Tracking System, with the help of this dashboard, also enables continuous improvement. Based on the identified discrepancies, corrective actions can be implemented. Adjustments to the construction schedule, resource allocation, or construction methods can be made. This not only helps in controlling the construction period risks but also enhances the overall efficiency of the project. Over time, as more data is collected from multiple projects, the system can be refined, making the BIM predicted metrics even more accurate and the risk tracking process more effective.

5.3.2. Lessons learned knowledge management

A BIM embedded database is established to capture risk mitigation best practices across industrial projects. This database serves as a repository for lessons learned, which is crucial for performance monitoring and continuous improvement in the BIM integrated project management process. During the pre-construction stage of industrial factory buildings, various period - related risks are identified and mitigated. The knowledge derived from these experiences is stored in the database. For example, if a particular BIM based scheduling optimization technique successfully reduced the impact of a potential risk on the construction period in one project, this practice can be recorded.

Project managers and team members can refer to this database to access the accumulated knowledge. It enables them to anticipate similar risks in new projects and adopt proven mitigation strategies. This not only saves time in the risk identification and solution seeking process but also enhances the overall efficiency of the project.

Moreover, as new projects are completed, more lessons are added to the database, creating a cycle of continuous improvement. The database thus evolves over time, becoming a more comprehensive and valuable resource for the industry. By effectively managing the lessons learned knowledge through the BIM embedded database, the control of construction period risks in the pre - construction stage of industrial factory buildings can be significantly enhanced, ensuring projects are completed on time and within budget.

6. Conclusion

In conclusion, this research on the control of construction period risks through BIM modeling optimization in the pre-construction stage of industrial factory buildings has achieved significant results. The case study projects have clearly demonstrated that systematic BIM modeling optimization can effectively reduce construction period risks by 32–41%. This finding is of great practical significance for industrial construction enterprises.

The proposed three phase implementation roadmap provides a clear and feasible guide for these enterprises. It enables them to better utilize BIM technology in the pre-construction stage, from initial model establishment to in depth optimization and finally to risk based decision making. By following this roadmap, construction companies can not only enhance their project management efficiency but also improve the predictability and controllability of the construction period.

Moreover, the application of BIM modeling optimization in the pre-construction stage is not only beneficial for individual projects but also has a positive impact on the entire industrial construction industry. It promotes the digital transformation of the industry, encourages more construction enterprises to adopt advanced technologies, and ultimately improves the overall competitiveness of the industry. Future research could further explore the integration of BIM with other emerging technologies, such as artificial intelligence and the Internet of Things, to further optimize the construction period control and risk management in industrial factory building projects.

Disclosure statement

The author declares no conflict of interest.

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Research on Key Points and Management Strategies for the Pre-Approval of Municipal Construction Projects

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Abstract: This article focuses on the pre-approval process of municipal construction projects, elaborating on its covered stages, functional positioning, etc. This paper introduces the key points of planning permission, environmental impact assessment and other links, discusses the innovation of management mechanisms, such as collaborative approval and BIM application, and also involves risk early warning, social stability assessment and other contents. It emphasizes the importance of technical review expert database and other aspects, verifies the effectiveness of management strategies and puts forward suggestions.

Keywords: Municipal construction; Preliminary review application; Management mechanism

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1. Introduction

The pre-approval process for municipal construction projects is a crucial link in the full life cycle management of the projects. Its significance lies in controlling the construction quality from the source, avoiding compliance risks and optimizing resource allocation. The review process covers core contents such as planning permission, land nature change, and environmental impact assessment, and must strictly follow the requirements of the overall urban planning and ecological protection. The current management mechanism is confronted with challenges such as insufficient cross-departmental collaboration and the need to improve approval efficiency. It is urgent to optimize the process by integrating technological innovation with policy guidance. According to the "Notice on Promoting the Standardization, Normalization and Facilitation of the Approval of Engineering Construction Projects" and the "Regulations on the Supervision of the Implementation of Territorial Space Planning", strengthening the application of digital platforms, promoting parallel approval and deferred acceptance systems have become the key points of reform. At the same time, it is necessary to improve the risk early warning and public participation mechanism, and enhance the efficiency of approval with policy support. Lay a solid foundation for the high-quality implementation of municipal construction.

2. Theoretical basis for preliminary approval of municipal construction projects

2.1. Basic process analysis of municipal construction projects

The entire life cycle of municipal construction projects covers multiple stages. From the initiation of the project, the necessity and feasibility of the project should be determined based on the urban development plan and actual needs [1]. In the early decision-making stage, a series of legal bases must be followed, such as relevant urban and rural planning laws, etc., to ensure that the project conforms to the overall development strategy of the city. In terms of administrative procedures, it is necessary to go through the preparation and approval of the project proposal, which elaborates and reviews the general outline of the project, the necessity of construction, etc. Next comes the feasibility study report stage, which requires in-depth analysis of the project in terms of technology, economy, environment and other aspects, including the comparison and selection of different construction plans. At the same time, environmental impact assessment is also a crucial step. It is necessary to evaluate the possible impacts of the project on the surrounding environment and propose corresponding measures. These processes and requirements have laid a theoretical foundation and standardized framework for the pre-approval of municipal construction projects.

2.2. Functional positioning of the pre-approval system

The pre-approval system for municipal construction projects has an important functional positioning. It is a key link in ensuring the quality and efficiency of municipal construction [2]. During the project initiation stage, strict approval can ensure the necessity and feasibility of the project and prevent blind construction from causing waste of resources. Land use planning approval can rationally plan land resources, make municipal construction conform to the overall development layout of the city, and improve land utilization efficiency. Environmental assessment and approval prompt projects to fully consider environmental impacts, take effective measures to reduce pollution, and achieve sustainable development. These pre-approval procedures are interrelated and mutually restrictive, jointly laying a solid foundation for the smooth implementation and high-quality completion of municipal construction projects. They control the direction and quality of municipal construction from the source and play an irreplaceable role in enhancing the comprehensive carrying capacity of the city and the quality of life of residents.

3. The core links of project approval in the early stage

3.1. Key points for the implementation of planning review and approval

In the planning permission stage of the early review of municipal construction projects, the change of land nature is of crucial significance. It is necessary to ensure that the change strictly complies with the requirements of the overall urban planning and relevant land use planning, and conduct a comprehensive assessment by fully considering factors such as the urban development direction, functional zoning and spatial layout. By scientifically analyzing the urban development strategy and regional functional positioning, the necessity and feasibility of changing land use should be reasonably determined to avoid blind adjustments that may lead to resource waste or functional imbalance. In terms of the approval of land use indicators, it is necessary to precisely calculate key indicators such as the area of construction land, green space ratio, floor area ratio, and building density, to ensure that all indicators comply with relevant national and local standards and regulations, while also taking into account the efficiency of urban space utilization and sustainable development goals [3].

For projects involving historical and cultural conservation areas or ecologically sensitive regions, special attention should be paid to the protection requirements of these special areas. They must strictly follow laws and regulations such as the "Urban and Rural Planning Law" and the "Regulations on the Protection of Historical and Cultural Cities, Towns and Villages", and carry out special reviews. The review content includes assessing the potential impact of the project on historical and cultural heritage, ecosystems and natural landscapes, and formulating targeted protection measures, such as restricting the construction scope and optimizing the design plan, to ensure that the project construction does not cause damage to cultural inheritance or ecological balance. Through standardized planning permission procedures and rigorous review mechanisms, a compliance foundation is laid for municipal construction projects, maintaining the sustainable development of the city's historical and cultural value and ecological environment.

3.2. Implementation norms for environmental impact assessment

Environmental impact assessment is a core step in the pre-approval process of municipal construction projects, ensuring that project implementation is in harmony with environmental protection. The preparation of environmental impact assessment documents should follow standardized requirements, comprehensively assess the potential impact of the project on environmental elements such as the atmosphere, water bodies, soil, noise and ecosystems, and ensure that the content is detailed and accurate based on scientific investigation and data analysis [4]. Advanced monitoring technologies and modeling methods should be adopted to accurately predict the environmental effects during the project construction and operation phases and identify key influencing factors. The public participation mechanism is an indispensable component of environmental impact assessment. Public opinions should be widely collected through various channels such as public hearings, questionnaires, and online public announcements to ensure the public's right to know and participate in the environmental impact of the project and enhance the transparency of decision-making. Environmental risk pre-assessment is equally crucial. It is necessary to systematically identify potential risk sources, such as pollutant emissions and ecological damage, analyze their occurrence probability and impact degree, and construct a risk assessment model. Based on the assessment results, targeted risk prevention and emergency measures should be formulated, such as optimizing construction techniques and setting up pollution control facilities, to ensure that environmental impacts are kept within an acceptable range. Through rigorous environmental impact assessment processes and scientific risk management, we provide environmental compliance guarantees for municipal construction projects, promoting a balance between ecological protection and urban development.

3.3. Special considerations in the preliminary approval of grassroots urban construction projects

3.3.1. Grassroots-level implementation of public participation

Grassroots projects are directly related to residents' daily lives, necessitating a shift from traditional public hearing and announcement methods to a more community-level, "on-the-ground" approach to communication. In collaboration with neighborhood committees, household visits and building-level meetings should be organized to focus on specific issues such as parking space planning and construction timing. A Summary of Residents' Opinions should be compiled and included as an attachment to the approval submission to prevent conflicts arising from public opposition at later stages. During the announcement phase, materials should be published simultaneously on community bulletin boards and WeChat groups, using plain language accompanied by illustrative diagrams. In communities with a higher proportion of residents aged 60 and above, dedicated personnel should be arranged to provide on-site explanations to ensure effective communication and feedback collection.

3.3.2. Hierarchical adaptation of departmental coordination

Grassroots units lack approval authority and must efficiently coordinate with district-level departments such as housing and urban-rural development, urban management, and environmental protection. A street-to-district approval liaison list should be established, specifying responsible offices, contacts, and material standards for each approval step to avoid repeated revisions due to formatting issues. For matters requiring multi-department approval, the “whistle-blowing and reporting” mechanism should be utilized to initiate joint site inspections and form a Joint Approval Opinion Form, thereby reducing cross-departmental communication time and ensuring the smooth progress of projects such as community fitness paths and renovation of old facilities.

3.3.3. Streamlined adaptation of material preparation

Given the limited technical capacity at the grassroots level, approval materials should adhere to the principle of “less but finer”. A checklist of materials categorized into “required” and “optional” items should be created, with exemptions granted for non-core materials in projects under 500 square meters. Streets should develop a Self-Checklist for Grassroots Approval Materials, focusing on verifying the authenticity of materials, alignment with overarching plans, and completeness of risk disclosures. This ensures that submission materials comply with regulations while reducing the burden on grassroots units and improving efficiency.

3.3.4. Livelihood-oriented risk prevention and control

Grassroots projects are prone to public sentiment risks related to construction disturbances and travel safety, necessitating pre-emptive risk assessment during the approval phase. A list of public opinion risks and corresponding response plans should be developed, with designated street contacts ensuring a 24-hour response mechanism. For projects involving historical buildings or ancient trees, cultural heritage departments must be engaged in advance for on-site verification and the issuance of an Avoidance and Protection Opinion to prevent approval rejection due to oversight of protected elements. This ensures both regulatory compliance and social stability.

4. Research on innovation of the review and approval management mechanism

4.1. Cross-departmental collaborative management mechanism

4.1.1. Integration of responsibilities of the approval department

In the innovation of the pre-approval management mechanism for municipal construction projects, it is crucial to establish a responsibility matrix model for collaborative approval among functional departments such as development and reform, housing and urban-rural development, and environmental protection. It is necessary to clarify the boundaries of responsibilities and collaboration mechanisms of each department to avoid delays in approval due to unclear responsibilities. The development and reform department is responsible for approving the feasibility study reports of projects, with a focus on reviewing whether the projects are in line with regional development plans and industrial policies to ensure strategic consistency. The housing and urban-rural development department focuses on reviewing the planning and design schemes, verifying their compliance with urban construction standards, spatial layout and technical specifications, and ensuring the quality of project implementation. The environmental protection department strictly controls the environmental impact assessment, evaluates the potential impact of the project on the ecological environment, formulates pollution prevention and control measures, and prevents adverse environmental consequences [5]. By establishing a responsibility matrix model, the approval tasks and connection processes of each department are clearly defined, and cross-departmental information sharing and collaborative decision-making are strengthened. Adopt digital management tools, integrate approval data, optimize process connections, and reduce repetitive review and communication costs. This mechanism not only enhances the efficiency of approval but also increases the transparency and standardization of decision-making, providing institutional guarantees for the efficient advancement of municipal construction projects and promoting the scientific and coordinated nature of the project’s entire life cycle management.

4.1.2. Construction of a digital approval platform

In the innovation of the pre-approval management mechanism for municipal construction projects, it is particularly crucial to establish a responsibility matrix model for collaborative approval among functional departments such as development and reform, housing and urban-rural development, and environmental protection.

It is necessary to clarify the boundaries of responsibilities and collaboration mechanisms of each department to eliminate approval delays caused by overlapping or ambiguous responsibilities. The development and reform department is responsible for approving the feasibility study reports of projects, with a focus on reviewing whether the projects comply with regional development plans and industrial policies to ensure consistency with the city's strategic goals [6]. The housing and urban-rural development department focuses on reviewing the planning and design schemes to verify whether they meet the urban construction standards, spatial layout requirements and technical specifications, ensuring the high-quality implementation of the projects. The environmental protection department strictly controls the environmental impact assessment, systematically evaluates the potential impact of the project on the ecological environment, and proposes effective pollution prevention and control as well as ecological protection measures to prevent environmental risks.

Through the responsibility matrix model, the approval tasks and process connections of each department are clearly defined, optimizing the efficiency of cross-departmental collaboration. Relying on digital management tools, approval data is integrated to achieve real-time information sharing, reduce repetitive review and communication costs, and enhance the transparency and standardization of processes. This mechanism significantly enhances the efficiency of approval, strengthens the scientific nature of decision-making, provides a solid institutional guarantee for the efficient advancement of municipal construction projects, and promotes the coordination and sustainable development of the entire life cycle management of projects.

4.2. Full-process standardized design

4.2.1. List-based management of approval requirements

Establishing a standardized template system for review materials classified and graded is an important measure for the list-based management of approval requirements. In view of the complexity and diversity of the preliminary review of municipal construction projects, by scientifically and reasonably classifying and grading the review materials, the efficiency and quality of the review can be improved [7]. Firstly, projects are classified based on factors such as their scale, nature, and investment amount. Different levels of projects are subject to different review standards and procedures. Secondly, classify the materials for review according to their categories, such as planning permission type, environmental assessment type, engineering design type, etc., and clearly define the specific requirements and format norms for each type of material. In this way, the units applying for review can clearly understand the content and standards of the materials that need to be prepared, and the approval departments can also conduct reviews more conveniently, reducing approval delays caused by non-standard or missing materials, thereby optimizing the management mechanism for the early review of municipal construction projects.

4.2.2. Dynamic adjustment mechanism for time limit control

The approval progress control model based on the critical path method is an important part of the innovation of the approval management mechanism for municipal construction projects. This model effectively controls the approval progress by analyzing various activities in the project approval process, determining the critical path and key activities. During the model construction process, it is necessary to fully consider the characteristics of municipal construction projects and the complexity of the approval process, and reasonably determine the time parameters and logical relationships of each activity. At the same time, a dynamic adjustment mechanism should be established. According to the actual progress of the project and changes in the external environment, the critical path and time parameters should be adjusted in a timely manner to ensure that the approval progress is always under control. By applying this model, the efficiency and quality of the approval management for municipal construction projects can be enhanced, the approval time and cost can be reduced, and a strong guarantee can be provided for the smooth implementation of the projects [8].

5. Optimization of the whole-process management strategy

5.1. Risk prevention and control strategies

5.1.1. Legal risk identification framework

The three-level risk early warning index system for administrative licensing compliance review is of vital importance to municipal construction projects. It is necessary to clearly define the first-level indicators, covering core contents such as the qualifications of the project entity and the completeness of the application materials. The qualification of the main body is directly related to the legality of project implementation. Any absence or non-compliance with qualifications may lead to the stagnation of the project. The completeness of the materials submitted for review is a prerequisite for ensuring a smooth administrative licensing process and must be strictly verified. The second and third-level indicators have been further refined.

Under the first-level indicators, the subject qualifications can be decomposed into specific requirements such as the validity period of the business license of the enterprise and the industry qualification level. The completeness of the review materials involves the standardization of the special report, the accuracy of the data and the compliance of the format. The third-level indicators are more specific, such as the matching degree between the business scope of the business license and the project requirements, and the technical depth of the environmental impact assessment report, etc. By establishing a three-level indicator system, the system identifies legal risks in the early review process, covering a comprehensive assessment from macro compliance to micro details [9]. This system provides a scientific basis for risk prevention and control by quantifying risk points and establishing early warning thresholds, ensuring the legal and compliant advancement OFL projects and laying a solid foundation for the efficient implementation of municipal construction.

5.1.2. Public opinion response plan

The disposal process for social stability risk assessment of major municipal projects is crucial for ensuring the smooth implementation of the projects. During the risk assessment stage, it is necessary to comprehensively analyze the potential impacts of the project on the surrounding environment, residents' lives, transportation, and social economy, etc. Scientific methods such as social impact assessment models should be adopted for quantitative analysis to accurately identify risk points. Once potential risks are identified, targeted prevention and control measures should be formulated immediately, including optimizing construction plans and strengthening environmental protection. For issues that may trigger public opinion, a real-time monitoring and early warning mechanism should be established, and big data and public opinion analysis tools should be utilized to track public attitudes and media dynamics [10]. When public opinion occurs, a prompt response is necessary. Accurate and transparent information should be released in a timely manner through official channels to address public concerns, clarify false rumors, and prevent social unrest caused by information asymmetry. At the same time, actively carry out public communication, widely collect opinions through forms such as symposiums and questionnaires, incorporate reasonable demands into the project optimization plan, and enhance public participation and satisfaction. This mechanism ensures that the project takes into account both social stability and public interests during its advancement, effectively reduces public opinion risks, and provides a guarantee for the efficient implementation of municipal construction projects and the harmonious development of the city.

5.2. Quality control strategy

5.2.1. Construction of the technical review expert database

To ensure the scientific and accurate nature of the preliminary review of municipal construction projects, it is of vital importance to establish a high-quality technical review expert database. It is necessary to take multiple approaches to clarify the selection criteria for experts, which should cover dimensions such as professional knowledge, practical experience, and professional ethics. In terms of professional knowledge, it is required that experts have in-depth attainments in related fields of municipal engineering, such as roads, bridges, water supply and drainage, etc. In terms of practical experience, one needs to have a certain number of years of actual project participation experience. At the same time, the professional ethics of experts should be emphasized to ensure that they can conduct reviews impartially and objectively. In the management of the expert database, a dynamic update mechanism should be established to regularly assess and evaluate experts, eliminate those who do not meet the standards, and replenish fresh blood. It is also necessary to improve the information management system of the expert database to facilitate the query, invocation and maintenance of expert information, thereby providing strong technical support for the pre-approval of municipal construction projects.

5.2.2. Full-process document traceability system

In municipal construction projects, establishing an approval process traceability management platform based on blockchain technology is important for the optimization of the entire process management strategy, quality control strategy, and the entire process document traceability system. The immutable feature of blockchain ensures that information at every stage of the approval process can be accurately and completely recorded. From the submission of project planning and design schemes to the feedback of approval opinions from various departments, all information is recorded in real time on the blockchain. This not only facilitates the project participants to check the approval progress and related documents at any time, but also provides reliable data support for quality control. Through detailed traceability of the approval process, potential problems can be identified in a timely manner, such as design modifications that do not comply with standards and unreasonable approval opinions, and corresponding measures can be taken to correct them, ensuring the smooth progress of municipal construction projects.

5.3. Efficiency improvement strategies

5.3.1. Innovation in the parallel approval model

In the early approval process of municipal construction projects, the development of an intelligent approval system architecture design that integrates multiple certificates is the key to the innovation of the parallel approval mode. The system should integrate the approval processes and standards of different departments to achieve information sharing and collaborative work. Through intelligent technologies, key information in the materials submitted for review can be automatically identified and extracted to enhance the efficiency of approval. Meanwhile, the system can set up an early warning mechanism to monitor the approval progress in real time and promptly identify and solve problems. In addition, a unified approval database should be established to store and manage the relevant information of all submitted projects, providing support for subsequent statistical analysis and decision-making. Such an intelligent approval system will effectively break down departmental barriers, simplify approval procedures, and enhance the management level and efficiency of the pre-approval process for municipal construction projects.

5.3.2. Optimization of the deferred acceptance system

Formulating detailed implementation rules for the supplementary commitment system of non-critical materials is an important measure to optimize the deferred acceptance system. First, it is necessary to clarify the scope of non-critical materials, which can be determined by assessing the importance and urgency of the materials submitted for review in the early stage of municipal construction projects. For these non-critical materials, a detailed supplementary commitment template should be formulated, including the time limit for supplementary submission, the responsible party, and the corresponding liability for breach of contract, etc. At the same time, an effective supervision mechanism should be established to ensure that commitments are truly fulfilled. During the implementation process, it is necessary to strengthen the guidance to the project units to ensure they fully understand the procedures and requirements of the supplementary commitment system. In addition, the implementation effect of the post-commitment system should be regularly evaluated and summarized. Relevant detailed rules should be continuously adjusted and improved based on the actual situation to enhance the efficiency and quality of the pre-approval process for municipal construction projects.

6. Conclusion

The pre-approval work for municipal construction projects is of vital importance, involving multiple key points and effective management strategies. Through the study of typical cases, the practical effectiveness of the constructed management strategy system has been verified, including shortening the approval cycle and reducing compliance risks, which provides a strong guarantee for the smooth progress of the project. On this basis, policy suggestions for establishing a credit evaluation system for the pre-approval of municipal construction projects are put forward, which is conducive to further standardizing the approval process and enhancing the sense of responsibility of relevant entities. Meanwhile, looking forward to the application and development direction of artificial intelligence-assisted decision-making in approval management, this may bring higher efficiency and accuracy to the pre-approval work of municipal construction projects, and promote the better development of the municipal construction industry.

Disclosure statement

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Analysis of Cost Control Strategies in Green Building Construction Processes

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Abstract: Green building construction typically incurs higher costs than conventional methods. To facilitate broader adoption by construction entities, cost optimization is essential. Firms must align with technological advancements, judiciously apply emerging technologies, and ensure resource efficiency through context-specific strategies. Proactive and precise scheduling is critical to avert delays from unforeseen events. Additionally, construction units should enhance on-site safety training, promote mastery of innovative techniques, and foster environmental awareness among personnel. Finally, companies ought to capitalize on government incentives for green materials while adopting bulk procurement from local sources to minimize transportation costs and secure lower unit prices.

Keywords: Construction process; Cost control; Strategy analysis

Online publication: Dec 12, 2025

1. Introduction

The construction industry plays a pivotal role in national economic development, while civil buildings serve as essential necessities for people's livelihoods. With growing public awareness of ecological protection, green building has garnered widespread attention across society [1]. Traditional construction processes often lead to environmental pollution and substantial waste of resources, adversely affecting the environment, economy, and residents' health. Consequently, many advocate for greening the construction process to achieve sustainable societal development [2]. Green building construction must ensure safety, prevent accidents, guarantee structural quality and longevity, while aligning with ecological civilization by minimizing environmental pollution [3]. Compared to conventional methods, green construction incurs additional costs in materials and emerging technologies, imposing financial burdens on enterprises. To enable firms to meet environmental protection requirements with minimal cost increments and alleviate operational pressures. Given the challenges posed by elevated costs in green building construction, exploring effective cost-control strategies is imperative. This paper examines technical, managerial, and market-oriented measures to address cost escalations arising from novel technologies and materials, thereby achieving overall cost containment.

2. Factors affecting the cost of green building construction

2.1. Technical measures

Technological innovation is a pivotal approach to mitigating elevated construction costs. Although novel materials are often pricier than conventional alternatives, their inherent energy-saving characteristics translate into operational cost savings during the building's lifecycle, ultimately yielding greater economic benefits compared to traditional construction.

A common issue during the construction phase is the failure of contractors to adequately assess the site's geological conditions, leading to an oversight and underutilization of inherent natural resources; in essence, failing to maximize the use of available materials. Furthermore, construction firms seldom utilize renewable energy sources, resulting in inefficient energy consumption.

To meet environmental protection standards during construction, units must implement innovative construction technologies. These advanced techniques encompass energy-efficient technologies, water-saving technologies, solid waste utilization technologies, low-carbon technologies, and intelligent monitoring systems. However, the high research and development (R&D) costs associated with these technologies, coupled with their procurement expenses, substantially drive up the overall cost for the construction unit. Moreover, the rapid iteration and replacement cycles of these advanced technologies further contribute to rising corporate expenditures.

In recent years, continuous advancements in science and technology have made it possible to effectively address these cost challenges through technological refinement and optimization.

2.2. Management level

Effective management and training of the workforce constitute a critical issue during the construction process. Construction firms must prioritize the health and safety of their personnel. Concurrently, they are required to embrace ecological civilization principles by adopting green construction methods to minimize pollutant emissions and maximize environmental protection, a requirement that inherently increases management complexity.

Common challenges in green construction include the workforce's unfamiliarity with new techniques and methods, as well as instances of laborers exhibiting a lack of awareness or commitment to environmental protection. These issues necessitate additional training investment from the construction unit. Furthermore, some firms suffer from insufficient detailed pre-planning, failing to anticipate potential risks or execute thorough inspections of construction materials. Such managerial deficiencies can trigger unexpected incidents, resulting in project delays or costly rework. All these management-related problems demand close attention from supervisory personnel to ensure the smooth execution of the construction process and on-schedule completion.

2.3. Market level

The market primarily influences construction costs through material pricing. Novel green materials, due to their superior environmental protection and energy-saving qualities, are generally priced higher than conventional materials, though their prices fluctuate within a certain range based on market demand.

To alleviate the financial burden on construction units, the government often introduces preferential policies aimed at lowering the price of new materials. This serves multiple goals: reducing corporate costs, promoting the adoption of innovative construction techniques, enhancing building quality, increasing market appeal, and boosting purchasing power. However, some construction units fail to recognize or capitalize on these government incentives or miss optimal material procurement timing, leading to avoidable cost escalations. Furthermore, instances of construction firms employing suboptimal procurement strategies can result in paying excessively high prices for raw materials, thereby increasing expenditure.

Therefore, it is crucial for construction units to consistently monitor and strategically utilize the available government preferential policies, while simultaneously adopting appropriate and cost-effective raw material purchasing methods. Nevertheless, a current issue is the relatively limited scope of government incentive policies and the insufficient penalty enforcement against firms engaging in severely polluting practices, which collectively contributes to the reluctance of construction units to fully adopt green building materials.

3. Strategies for cost control in green building construction

3.1. Technology-level strategies

Technological refinement for cost control primarily involves three key approaches: adopting Passive Building Energy-Saving Technologies, utilizing Renewable Energy Sources, and effectively employing Building Information Modeling (BIM) technology.

Passive Building Energy-Saving Technologies involve leveraging natural resources based on specific regional climates and geological conditions to maintain optimal indoor temperature, humidity, and ventilation [4,5]. This approach allows construction to be site-specific and maximize resource utilization. It provides construction units with various methods for exploiting natural resources, such as natural ventilation, daylighting, and the reuse of construction waste [1]. These methods contribute to more streamlined construction and lower costs.

The use of renewable energy sources is an essential tool for cost control. Systems like solar water heaters and air-source heat pumps provide hot water by harnessing solar or natural energy (air heat storage), respectively. Utilizing these abundant and easily accessible renewable natural resources meets the requirements for both cost reduction and environmental sustainability [4]. Furthermore, instead of direct disposal, construction waste should be considered for recycling and reuse, with surplus materials being reserved for subsequent projects.

BIM technology is a common technique used in green building construction. BIM enables precise modeling, accurate calculation of required material quantities and costs, pre-assessment of potential issues during the actual construction process, and the development of optimized construction plans [6]. This allows construction units to identify problems proactively, find rational solutions, mitigate risks, and minimize losses. Additionally, BIM can analyze multiple scenarios to identify the most cost-effective construction plan, thereby achieving the goal of cost savings.

Based on the perspective of adopting advanced scientific and technological methods, this paper introduces the application of energy-saving elevators in practical scenarios, focusing on two examples: the Permanent Magnet Gearless (PMG) elevator and the Electro-Hydraulic Hybrid Drive Traction Elevator with a variable displacement pump/motor.

For typical elevators, a significant amount of power is consumed during motor rotation, with a portion of this energy dissipating as both electrical and thermal energy. A common feature of both these advanced elevator types is their ability to recover substantial amounts of clean electrical energy. This recovered energy can account for 30% to 70% of the total energy consumed during the elevator’s operation. Furthermore, the energy recovery efficiency, especially through the pump/motor recovery method, can exceed 90% [4,7]. This regenerated energy can be fed back into the building’s power grid via an accumulator, allowing the electricity to be reused by the elevator. This approach not only reduces energy waste but also lowers the temperature inside the elevator cabin, enhancing user comfort and experience [4].

The fundamental objective of employing energy regeneration technology is ultimately cost saving. From a unit price perspective, the cost of a new energy-regenerating elevator is comparable to that of a traditional elevator, both being around 6,000 RMB per unit. However, in terms of power consumption, the new energy-regenerating elevator offers a distinct advantage, reducing consumption from the original 1872 kW/h to approximately 1 kW/h. This dramatically increases energy utilization efficiency, conserving energy and lowering operational costs [4].

In a separate study, experiments conducted on the Electro-Hydraulic Hybrid Drive Traction Elevator with a variable displacement pump/motor (as shown in **Table 1**) demonstrated its excellent energy-saving performance. Moreover, the energy-saving effect was observed to initially decrease and then increase as the load increased. This indicates that the energy-saving benefits of these elevators are greatest when carrying either very few or very many passengers.

Table 1. Relationship between load and energy-saving effect for the electro-hydraulic hybrid drive traction elevator with variable displacement pump/motor

Load / kg	Energy-saving effect / %
100	36.9
300	8.4
700	10.6
900	39.2

3.2. Management-level strategies

The most critical subjects of management during the construction process are the site personnel. Construction units must prioritize the safety of the workforce, emphasize the selection of experienced workers, and strengthen their safety training. Concurrently, site security must be ensured to prevent accidents.

It is necessary to intensify skills training for personnel, ensuring they learn to operate novel equipment and can apply it proficiently during construction. Workers must also be educated against the arbitrary disposal of construction waste to raise their environmental protection awareness. Furthermore, dust and exhaust fumes generated during construction must be handled appropriately to prevent environmental contamination.

Indoor air quality and pollutants generated by building materials and the construction process must also be monitored. The presence of residual pollutants, such as formaldehyde, in the finished structure could negatively impact the occupants' health, thereby failing to meet green building standards. During nighttime operations, construction units should avoid using excessively bright lighting and control construction noise by minimizing the use of large-scale mechanical equipment. This approach reduces light and noise pollution, achieving the environmental benefits of green construction [3]. Such practices minimize negative impacts on nearby residents while safeguarding the health of the construction workers.

To further ensure worker health, construction units should monitor weather forecasts to prevent heatstroke during high-temperature periods. Relevant authorities have also mandated specific working hours based on temperature conditions to reduce the risk of on-site accidents.

Construction units must also proactively plan the construction schedule to account for potential delays caused by environmental factors such as high temperatures or heavy rainfall, which could halt normal operations and jeopardize the timely completion of the project. This requires construction management to motivate workers to maintain an efficient and diligent pace, while simultaneously preparing for unforeseen circumstances by allocating both buffer time and contingency funds.

Furthermore, construction units must ensure the quality of construction materials by strictly inspecting every component to confirm it meets project specifications and pre-defined quality standards. This is essential to prevent safety incidents arising from material failure or the need for costly rework due to substandard quality, which would undermine the on-time delivery of the project [2]. Finally, the construction unit should closely monitor the project budget, regularly reviewing expenditure against the cost plan, and making timely adjustments to construction strategies as needed.

3.3. Market-based approaches

This section primarily analyzes the market's influence on costs from the perspective of raw material procurement.

It is essential to conduct a thorough evaluation of potential material suppliers to secure a stable, reliable source that complies with green building requirements. The selected supplier must offer materials that are quality-assured, reasonably priced, and highly regarded within the industry, ensuring the durability of materials put into use and eliminating safety risks [6]. Construction units must also develop the discernment necessary to assess the quality of materials and equipment, emphasizing a refined selection process.

To achieve cost efficiency, firms should implement centralized, bulk procurement of common equipment and materials. By establishing long-term partnerships with fixed suppliers, construction units can secure volume discounts and subsequently reduce the unit price of materials [6]. Furthermore, sourcing raw materials from regions near the construction site is critical to minimize transportation costs and time [6]. Firms should also evaluate market supply and demand dynamics to purchase materials when prices are at a low point, thereby maximizing cost savings.

Construction units must pay close attention to government-issued preferential policies and leverage these incentives to achieve cost savings. To encourage the use of green building materials in construction, the government has introduced various supportive policies, such as reductions in Value-Added Tax (VAT) and Consumption Tax. For instance, taxpayers selling self-produced new wall materials listed in the Catalogue of New Wall Materials Eligible for VAT Refund-upon-Collection Policy are entitled to a 50% immediate refund of VAT collected. Additionally, the Consumption Tax is waived for the production, commissioned processing, or import of coatings with a volatile organic compound (VOC) content below 420 g/L in their application state. These policies can effectively reduce the operational costs for construction units.

The government also needs to expand the scope of tax reductions and exemptions for construction units that implement green construction practices, introducing a greater variety of preferential policies. Furthermore, it is essential to fully implement the specific guidelines within green construction regulations, making the construction standards clearer and more detailed. Severe penalties should be enforced against firms that cause significant environmental pollution. By establishing a clear system of rewards and punishments, more construction units will be incentivized to adopt green building construction methods [1].

4. Conclusion

Technical improvements in green building construction processes are diverse. Construction entities should prioritize keeping pace with technological advancements, selectively adopting novel methods tailored to their specific needs. This approach enables the practical implementation of green building construction, while simultaneously enhancing residents' living environments, reducing construction costs, and conserving energy. Emphasis must also be placed on construction management, including elevating workers' technical skills and environmental awareness. Advance planning is essential to ensure material quality, complemented by rigorous on-site inspections to prevent rework.

Construction entities should leverage government incentive policies effectively, formulate procurement plans aligned with market prices, and proactively incorporate green building materials to achieve cost savings.

With ongoing advancements in science and technology, cost-control methods for green building construction processes will proliferate. In the future, construction entities will be able to identify optimal strategies from this expanding array to minimize project expenses and generate additional exemplary cases of cost efficiency in green building practices, yielding greater benefits for both entities and residents. Governments should establish clear reward-and-penalty mechanisms to promote green construction and penalize environmentally damaging practices.

Disclosure statement

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Research on the Evaluation of Risk Control Schemes for Engineering Projects under Uncertain Environments

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Abstract: To effectively select risk control schemes in uncertain environments, this paper has proposed an analysis and evaluation method based on the fuzzy comprehensive evaluation method. Firstly, enterprises have adopted the brainstorming method and the Delphi method to identify risks in engineering projects, and organized the identified risks in the form of checklists to facilitate further analysis. Secondly, the fuzzy comprehensive evaluation theory was introduced to determine the comparison matrix of each risk factor and its weight. Furthermore, the top five risk factors in terms of weight ranking were taken as the evaluation factors for the selection of risk control plans. The plans were scored through the weighted scoring method, and the optimal risk control plan was determined based on the score. Finally, the feasibility of the proposed selection technology was verified through A research example of the risk control plan assessment for the construction project of Enterprise A.

Keywords: Engineering projects; Fuzzy comprehensive evaluation method; Uncertain environment; Risk control schemes

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1. Introduction

Engineering projects in the construction industry need to go through stages such as design, planning, construction, and completion acceptance. However, the uncertainty and complexity of the situation have increased the difficulty of risk control in construction projects. During this process, how to effectively carry out risk control before the commencement of engineering projects and how to select the best risk control plan are the key procedures, which are of great significance for the smooth completion of the subsequent stages. The fuzzy comprehensive evaluation method can quantify the identified risks of engineering projects. By constructing a judgment matrix through the fuzzy comprehensive evaluation method, the maximum eigenvalue and eigenvector were calculated as the weights of each risk factor. The risk danger was ranked according to the size of the weights, and the evaluation factors are determined for the selection of risk control plans. Therefore, this paper has proposed the research on the assessment of project risk control schemes based on the fuzzy comprehensive evaluation method in an uncertain environment, further provided enterprises with a risk control scheme centered on project quality and offering a new idea for each enterprise to select the optimal risk control scheme.

Risk management was referred to the need to formulate corresponding contingency plans for the constantly changing risks in the risk prevention process during the management process, ensuring timely response. In the face of new risk issues, timely assessment and evaluation should be conducted, so as to make appropriate adjustments to the risk management emergency plan and ensure that the new plan can be effectively implemented during the construction process. Ensure that there is a complete risk monitoring plan for each stage of the entire project construction to maintain the dynamic and continuous nature of risk prevention throughout the project construction period, thereby achieving the predetermined prevention effect. Risk identification for large-scale projects and classified the risks were conducted, dividing them into technical and non-technical risks, which is of positive significance for the implementation of risk identification [1]. The content of engineering risk quantification and quantified the relevant risks were proposed, which is helpful for identifying the related risks [2]. The inquiry method was adopted to make the risk list by consulting relevant experts [3]. The checklist method was used to confirm the risk factors of actual cases, that is, risk identification [4]. The Analytic Hierarchy Process (AHP) and fuzzy analysis method was employed to assess and analyze project risks [5]. Its advantage lies in the fact that when evaluating project risks, it can meticulously analyze the impact degree of each risk factor on the entire project, enabling targeted measures to be taken.

The main research content of this article is as follows: Firstly, it has analyzed the positive significance of the selection of risk control schemes in enterprise construction projects. Secondly, from the perspective of risk identification, combined with the common risk contents of enterprise construction projects, the common risks in enterprise construction projects were summarized and sorted out by using methods such as brainstorming, Delphi method and checklist method. Furthermore, based on the identified risks, various risks were evaluated and analyzed from different perspectives using the fuzzy Analytic Hierarchy Process, and specific evaluation results were provided. Finally, for the identified risks, as the evaluation factors of the risk control plan, the weighted scoring method was adopted in combination with the actual case A enterprise construction project risk management research. Through the application of the above risk identification, evaluation and analysis as well as the selection of risk control plans, the above research was improved.

2. Selection methods for risk control plans in engineering projects

The main focus in this article was on the assessment of risk control plans during the construction process of ongoing engineering projects. The objective was to adopt scientific and reasonable methods to identify the main risk factors of construction projects, assess and analyze them, and take appropriate control decisions to reduce risks. The existed risks were unable to be completely avoided. Hence, new strategies were required to control them within an acceptable range through scientific management methods [6]. Based on this, a method for selecting risk control schemes for engineering projects was proposed (refer **Table 1**).

(1) In the process of risk identification for construction projects, the brainstorming method was first adopted to have relevant experts and practitioners identify related risks based on the current situation, and then the identified risks were made into a table, which is the risk checklist. Through this checklist, relevant risks were relatively well identified.

(2) Five managers, five technical engineers and five supervision experts with over 10 years of experience in the industry were selected. The Delphi method was used to have the relevant experts evaluate the identified risks. The opinions of the experts were summarized and the risk factors that the experts all

considered to constitute risks were recorded. After the opinions of the experts tend to be consistent, the relevant factors that the experts consider to have a relatively high risk were scored. The scoring was mainly focused on the occurrence probability of the relevant risk factors. Let the above-mentioned experts score the relevant indicators and take the average value to represent it using the 9-level scaling method. After scoring, a first-level comparison matrix was obtained. Through calculation, the first-level comparison matrix yields the scores of relevant risk factors. After meeting the consistency test, the relative importance levels of each risk factor were obtained.

Table 1. Comprehensive evaluation matrix $\boldsymbol{R}=\left(r_{ij}\right)_{N\times M}$ of alternatives

Plan	G_1	G_2	…	G_M
S_1	r_{11}	r_{12}	…	r_{1M}
S_2	r_{21}	r_{22}	…	r_{2M}
…	…	…	…	…
S_N	r_{N1}	r_{N2}	…	r_{NM}

$$b_{ij}=ln\left(1/a_{ij}\right)\ (i=1,2,\ldots,N,\quad j=1,2,\ldots,M) \tag{1}$$

$$Z_i=\sum_{j=1}^{M}\rho_{\text{nom}j}b_{ij}\ (i=1,2,\ldots,N,\quad j=1,2,\ldots,M) \tag{2}$$

(3) The standard scale scoring method was used to determine S. This method has usually provided different standard scoring values, such as 1–5 or 1–10 points, and used the size of the score to determine the degree to which the scheme meets the evaluation objective. Based on the weights obtained from the expert evaluation team information, the comprehensive information volume of the alternative plans was calculated, and its calculation formula was shown below.

$$R_i=\sum_{j=1}^{M}Z_i s_{ij}\ (i=1,2,\ldots,N,\quad j=1,2,\ldots,M) \tag{3}$$

Risk identification was conducted for engineering projects by adopting the brainstorming method. After risk identification, the Delphi method was used to reanalyze the previously determined risks, that is, to quantify the risks. Then, the fuzzy analytic Hierarchy process was used to create a judgment matrix. Finally, the weights were processed to determine the risk level. The optimal risk control plan was selected through the weighted scoring method.

3. Examples and analysis of results

Although the construction project of Company A has involved in the expansion of the company's factory buildings and dormitories, the main project was still a building project. It has similar characteristics to general construction projects and thus has a certain degree of universality. Then, during the risk analysis of the construction project of Company A, general construction project cases was referred to. Meanwhile, the analysis and evaluation research of the risk control plan of the construction project of Company A have provided a reference for the relevant analysis of other construction projects to a certain extent. In accordance with the content of the risk control plan selection method, starting from risk identification, evaluation and analysis. A further analysis of this project was conducted. Based on the relevant contents of risk identification and evaluation analysis, the risk control plan for the construction project of Enterprise A was selected.

(1) From the risk checklist of the engineering project design stage, it was known that during the design stage of the construction project of Company A, this study has focused on identifying the risks of process and flow, technical and usage risks, the rationality of design, the accuracy of background information, and risks related to the working environment. On the basis of these identified risk factors, this study has further refined the analysis.

(2) Due to the excessive number of risk factors proposed by the project team of Company A during the brainstorming session, this study has identified and analyzed these risk factors. By re-analyze the contents of the risk checklist mentioned above through the Delphi method, and select managers, technicians, and supervisors with over 10 years of experience in this industry, risks have been identified. The risk factors that all experts consider to constitute risks have been identified, as shown in **Table 2**.

Table 2. The main risks of engineering projects and the weights

The main risks	Contents of risks	The weights
Materials of equipment	The quality, progress and personnel safety of construction projects are affected due to the substandard construction machinery and building materials	C1 (0.147)
Safety risk	The prevention measures are inadequate and the risk control plan is incomplete	C2 (0.196)
Personnel risk	Insufficient safety awareness among on-site construction workers	C3 (0.657)
Policy risk	Refers to changes in relevant government policies	C4 (0.122)
Financial risk	The risk caused by excessively high procurement costs of materials	C5 (0.558)
Quality management	Materials and equipment were substandard	C6 (0.320)
Contract risk	Risks arise due to loopholes in the contract	C7 (0.494)
Supplier management	Risks arising from suppliers' non-compliance with contracts	C8 (0.266)
Design plan	Implemented in accordance with laws and regulations	C9 (0.240)
Technology	Technologies cannot be utilized	C10 (0.230)
Economic risks	The overall situation of the financial market	C11 (0.648)
The working environment	The climate, water quality and other conditions at the construction site	C12 (0.122)

Based on the relevant analysis of the weight ranking of risk factors, it was concluded in the first-level risk factor indicators that management risk was higher than technical risk, technical risk was higher than construction risk, and construction risk was higher than environmental risk. According to Equation (1) and (2), the most significant risk factors for Company A's construction projects were: technical and operational risks, political risks, contract management, equipment and materials, supplier management, and safety risks.

(3) Considering the actual situation of the engineering project, the expert team has determined three alternative risk control plans for the construction project of Company A and has selected five employee representatives (D1 to D5) from among the numerous employees of Company A to evaluate the three alternative plans. Based on the risk factor analysis and evaluation of the construction project of Enterprise A, it was concluded that the risk factors affecting the project was divided into two layers. The first layer was the project layer, and the second layer was the criterion layer, mainly the specific factors that have an impact on the project. The weight ranking was obtained by the fuzzy comprehensive evaluation method. Select the top five as the key evaluation index factors for the weighted scoring method. Factor set F = {F1: Technology and Application, F2: Policy Risk, F3: Contract Management, F4: Equipment and Materials,

F5: Supplier Management}. The normalized index weight vector was obtained by using the improved weighted average method as $\tilde{\boldsymbol{n}}_{\text{norm}} = (0.20, \quad 0.14, \quad 0.22, \quad 0.31, \quad 0.13)$.

(4) The expert team thoroughly analyzed the existing scheme information. Five experts have reviewed the initial design values of the scheme to obtain the evaluation values. The experts have obtained the relative weights of each expert through voting. Based on the expert weights, the comprehensive evaluation values were obtained to construct the evaluation matrix (**Table 3**).

Table 3. The evaluation information of five alternatives

	R_1	R_2	R_3
D_1	0.46	1.00	0.76
D_2	1.00	1.00	0.77
D_3	0.38	1.00	0.73
D_4	0.63	1.00	0.83
D_5	0.00	0.00	1.00

Based on Equation (11), the comprehensive assessment values of the alternative risk control plan for this project were obtained as: $R_1 = 2.57$, $R_2 = 3.54$, $R_3 = 3.53$. Therefore, R_2 was the optimal risk control scheme.

To further verify the effectiveness of the method, after the enterprise applied the results and analyzed the feedback information from the project implementation department, the results were recognized. The application of this method also indirectly brought the following benefits to the enterprise: It has reduced problems such as project delays, cost overruns, and substandard quality, lowered economic losses and resource waste, safeguarded the rights and interests of all parties involved in construction, operation, and supervision, and avoided disputes. At the same time, by optimizing processes and standardizing operations, the project management level was enhanced to accumulate reusable experience for subsequent projects and ensure the smooth fulfillment and delivery of the projects.

4. Conclusions

Based on domestic and international research and in accordance with the actual situation of engineering enterprises in China, this paper has analyzed the main influencing factors of digital transformation of engineering enterprises, and has constructed an evaluation index system for the maturity of digital transformation of engineering enterprises from four aspects, by using the G_1 method to obtain the index weights, and finally applied the cloud model to evaluate the maturity of digital transformation of engineering enterprises.

(1) Based on current standards and norms, this paper has analyzed the influencing factors of digital transformation in engineering enterprises by establishing index principles and bases, and uses principal component analysis to screen the influencing factors of digital transformation in engineering enterprises, eliminating secondary indicators An evaluation index system for the maturity of digital transformation of engineering enterprises has been established, which includes four first-level indicators: digital operation technology, digital system guarantee and digital foundation, and digital performance, nine second-level indicators, and 24 third-level indicators.

(2) By using G_1 to calculate the weights of the evaluation indicators for the digital transformation maturity of engineering enterprises, it can be understood that the degree of influence of intelligence level, total factor productivity, digital strategy formulation, digital strategy matching, and management decision-

making efficiency on the digital transformation maturity of engineering enterprises is relatively large. Corresponding measures can be taken during the digital transformation process. Accelerate the digital transformation of engineering enterprises.

(3) This paper has employed a cloud model to evaluate the maturity level of digital transformation in engineering enterprises, which can effectively address the ambiguity and randomness of the evaluation, complete the conversion between qualitative expression and quantitative values of maturity evaluation, and make the evaluation more objective and reasonable.

Disclosure statement

The author declares no conflict of interest

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Study on Asymmetric Deformation Patterns in Layered Soft Rock Tunnels

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Abstract: Layered rock mass is a typical complex rock mass. Owing to its layered structure, its deformation and strength properties exhibit distinct anisotropic characteristics. Taking a deep-excavated railway tunnel as the engineering context, this study investigates the asymmetric deformation laws of layered soft rock tunnels from two perspectives: laboratory tests and numerical simulations. Uniaxial saturated compression tests were conducted to analyze the anisotropic mechanical characteristics of rock bedding planes. This study established a model of layered rock mass tunnel excavation and support. From the perspectives of tunnel peripheral displacement, plastic zone, and maximum principal stress, it reveals the asymmetric deformation characteristics of the surrounding rock under different dip angles of bedding planes. These findings provide valuable insights for the construction of high-stress layered soft rock tunnels.

Keywords: Layered soft rock tunnels; Carboniferous slate; Asymmetric deformation; Anisotropy

Online publication: Dec 12, 2025

1. Introduction

1.1. Background

Railway tunnel construction often faces the impact of high in-situ stress, high seismic intensity, and complex tectonic stress fields. Beyond these challenges, a common characteristic is traversing stratigraphic formations composed of carbonaceous shale, phyllite, and other layered, weak strata. These formations exhibit poor mechanical properties and low self-stabilizing capacity, leading to issues such as spalling and failure of initial support, as well as distortion and deformation of rigid arches. These issues pose significant challenges to both the construction and operation stages of the tunnel. Existing research has established a fundamental theoretical framework for the deformation mechanisms of layered soft rock, with existing research primarily focusing on lateral pressure issues caused by topography and weak interlayers [1–12]. However, the constitutive behavior of the surrounding rock remains the dominant factor governing the evolution of large deformations. Based on a deep-excavated railway tunnel, this paper studies and analyzes the influence of bedding plane occurrence on the asymmetric deformation laws of layered soft rock tunnels by means of laboratory tests and numerical simulations.

1.2. Project overview

The tunnel is a high-altitude double-track, twin-bore railway tunnel. The portal elevation is approximately 2,735 meters, while the exit elevation is approximately 3,260 meters, presenting an elevation difference of 525 meters. The track spacing is 45 meters, with a maximum burial depth of approximately 670 meters. The surrounding rock is complex and variable in lithology, predominantly consisting of slate with local intercalations of sandstone. The schist exhibits a predominantly microcrystalline mudstone texture with localized sandy structures, exhibiting extremely thin-bedded formations typically less than 1 cm thick. Inter-bedding cohesion is poor, classifying it as weak rock mass. This poses a significant risk of large deformation due to compression during excavation. The tunnel zone traverses strata within joint zones and densely jointed areas, predominantly oriented NE with predominant dip directions of 100° to 150°, generally exhibiting steep dip angles. Joint spacing generally ranges from 0.5 to 2.0 meters, with extensions exceeding 1.0 meter. Most joints are either closed or slightly open, lacking infill and exhibiting relatively straight orientations. Statistical analysis of joint dip directions and dip angles for the Triassic Longwu River Formation is presented in **Figure 1**. In-situ stress testing was conducted across 29 measurement sections within six deep boreholes in the tunnel zone. As shown in **Figure 2**, the maximum horizontal principal stress reached 22.88 MPa, classifying this as a high-to-extremely high in-situ stress zone.

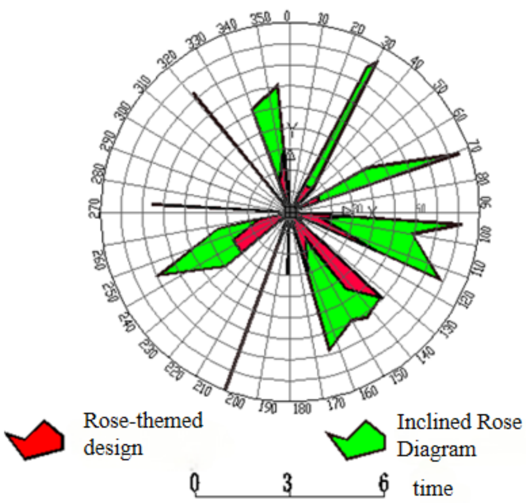


Figure 1. Rose-shaped joint pattern.

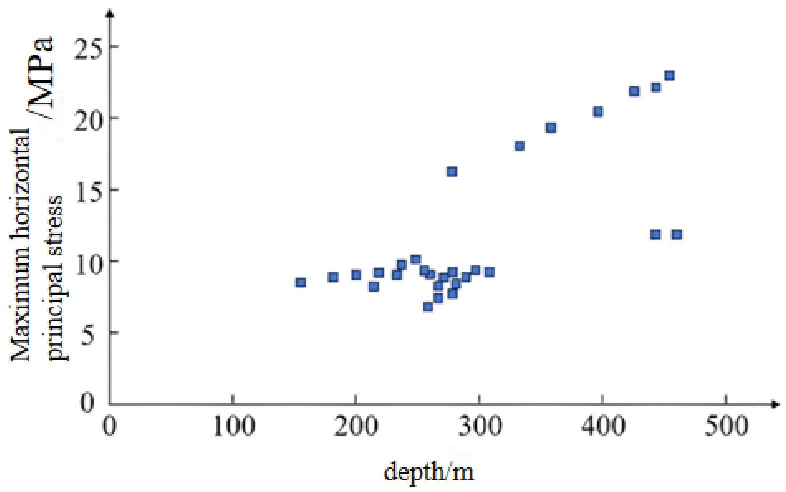


Figure 2. Relationship between maximum horizontal principal stress and tunnel depth.

2. Rock mass mechanical properties

To investigate the mechanical properties of rock blocks with varying bedding plane angles, thin-bedded jointed rock blocks predominantly composed of carbonaceous shale were selected. All specimens were extracted from the same excavation cross-section within the tunnel. Owing to the distinctive thin-bedded sedimentary structure of carbonaceous slate, the sampling success rate was low, and the specimens were not derived from a single block. Carbonaceous slate specimens were drilled at five angles: 0°, 30°, 45°, 60°, and 90°. The specimens were cylindrical in shape, with a diameter of 50 mm and a length of 10 mm, tolerances of ± 0.5 mm, and end-face parallelism of ± 0.02 mm. Uniaxial saturated compressive strength tests were conducted on carbonaceous slate specimens with different bedding plane orientations. The results obtained from these tests are presented in **Figure 3**.

dip	dip-0°	dip-30°	dip-45°	dip-60°	dip-90°
Ultimate compressive strength/MPa	23.12	16.67	9.44	18.87	37.35
Secant Elastic ModulusE50/GPa	23.07	4.98	4.20	4.58	34.52

Figure 3. Mechanical properties of specimens at different inclination angles.

The test results indicate

(1) The ultimate compressive strength and secant modulus of rock specimens obtained from uniaxial compression tests reveal pronounced anisotropic mechanical properties in layered carbonaceous shale. Analysis of failure characteristics across different bedding plane orientations indicates that the weak bedding planes constitute the primary factor influencing the rock mass's anisotropic mechanical behavior. The uniaxial saturated compressive strength and secant modulus of the rock blocks exhibit a U-shaped variation with respect to the bedding plane angle.

(2) When the loading direction is parallel to the bedding plane (bedding plane angle 90°), both the ultimate compressive strength and secant modulus are greater than when the loading direction is perpendicular to the bedding plane (bedding plane angle 0°). At a bedding plane angle of 45°, both ultimate compressive strength and tangent modulus of elasticity attain their minimum values. The uniaxial saturated compressive strength of rock blocks at different angles provides a partial explanation for the occurrence of buckling failure in tunnels through layered soft rock.

3. Study on the physical field characteristics of three-layered soft rock tunnels

3.1. Stratigraphic-structural model and selection of constitutive parameters

The Ubiquitous-Anisotropic model is based on the Mohr-Coulomb constitutive relationship, adhering to the Mohr-Coulomb yield criterion. It incorporates anisotropic constitutive behavior by embedding weak planes oriented in specific directions. The geological formation traversed by the tunnel consists of carbonaceous laminated schist, exhibiting pronounced anisotropic mechanical characteristics. Physical and mechanical parameters of the rock mass were determined in accordance with the Technical Specification for Railway Tunnels in Compressible Surrounding Rock. A ubiquitous jointed constitutive model was employed to simulate the excavation of a layered soft rock tunnel, with the parameters used for simulation shown in **Table 1**.

Table 1. Constitutive parameters

Constitutive parameters	Unit	Parameter range
dip	°	0–90
dip-direction	°	90
joint-cohesion	MPa	0.6
joint-friction	°	25
joint-tension	GPa	0.18
young-plane	GPa	1.2
young-normal	GPa	0.5
poisson-plane	/	0.4
poisson-normal	/	0.2
density	kg/m^3	2000

The computational model employs the actual cross-sectional dimensions of the tunnel, as illustrated in **Figure 4**. Support parameters are classified as Grade V, with the tunnel buried at a depth of 600 meters. The fundamental assumptions for the geological-structural model are as follows:

(1) Both stress and strain in the strata and support parameters remain within the elastic-plastic range

(2) The influence of tunnel excavation on rock mechanical parameters is disregarded

(3) The effects of groundwater seepage are not considered

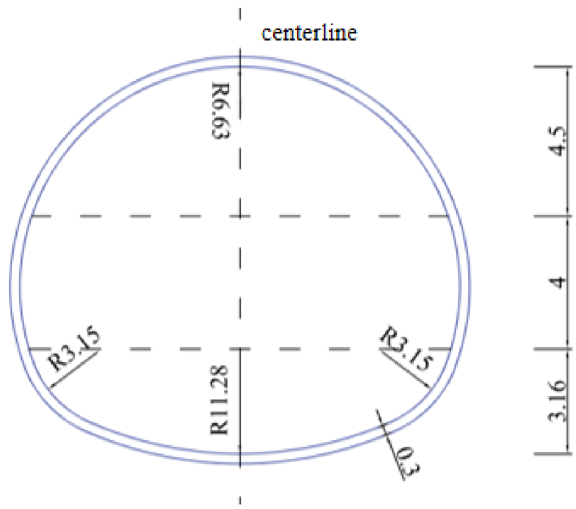
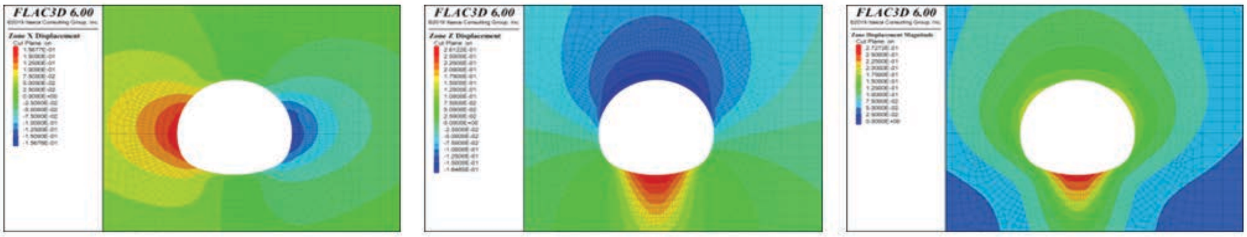


Figure 4. Tunnel cross-section diagram.

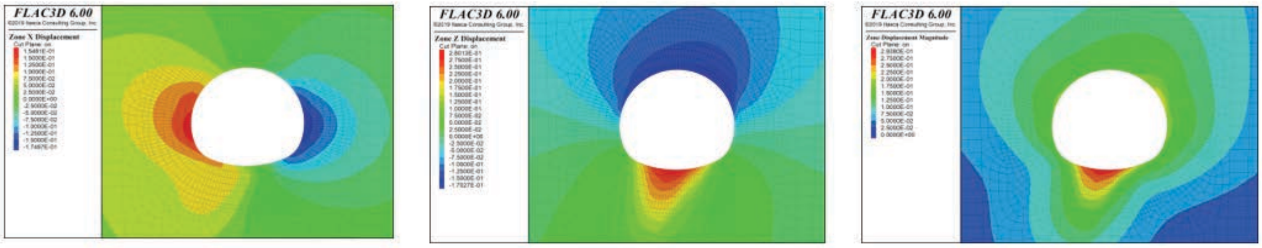
3.2. Perforation displacement

Following completion of the tunnel excavation, horizontal displacement, vertical displacement, and combined displacement contour plots under different inclination conditions for the same stratigraphic plane inclination were selected at the mid-section (Y = 60 m), as shown in **Figures 5** to **11**.



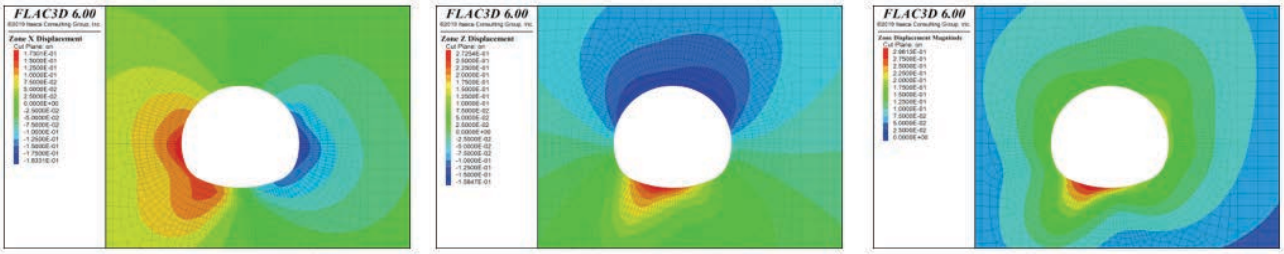
(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 5. dip-0°.



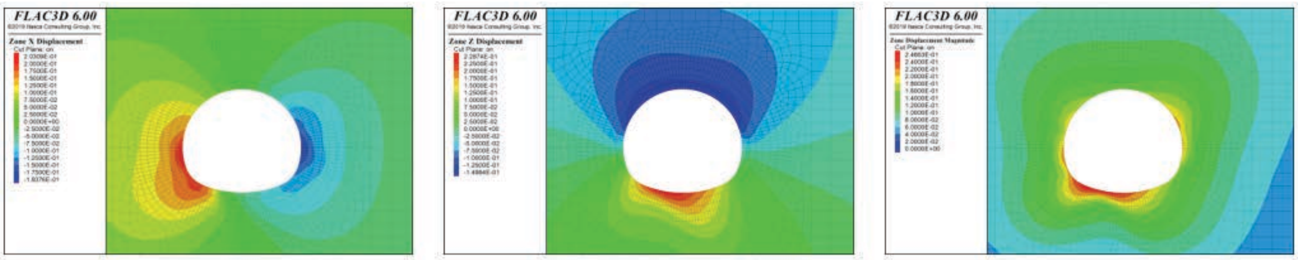
(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 6. dip-15°.



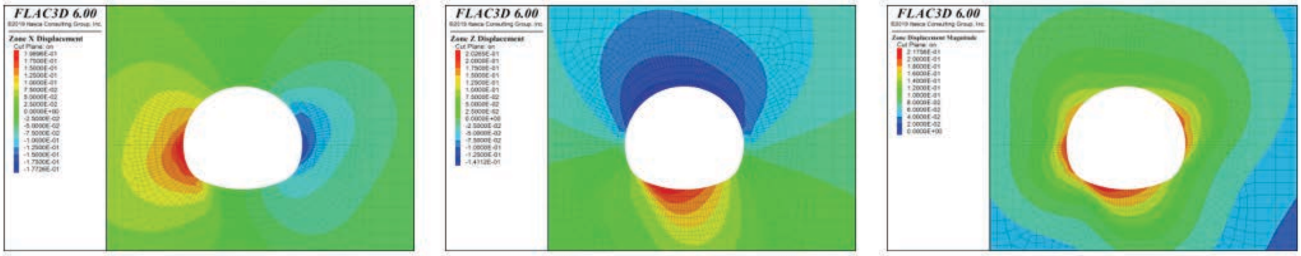
(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 7. dip-30°.



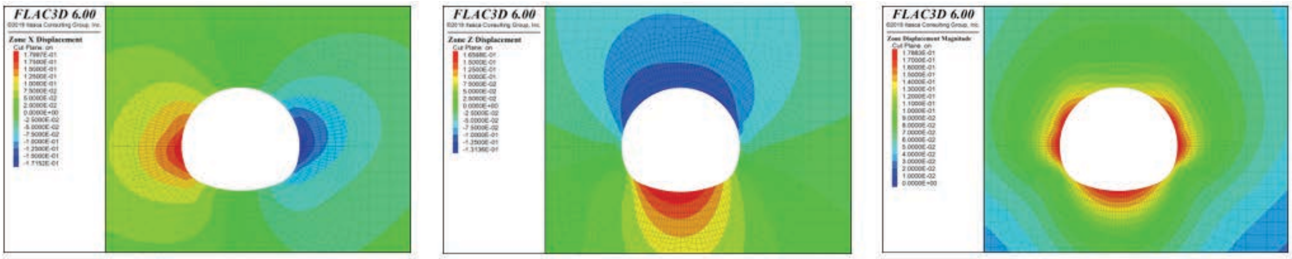
(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 8. dip-45°.



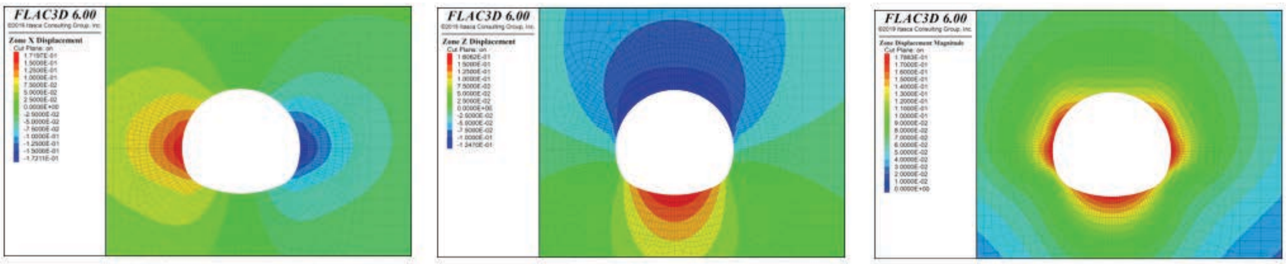
(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 9. dip-60°.



(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 10. dip-75°.



(a) Horizontal displacement (b) Vertical displacement (c) Resultant displacement

Figure 11. dip-90°.

From the deformation characteristics observed around the rock cavities at different stratigraphic dip angles (see **Table 2**), it can be seen that:

(1) The deformation characteristics of the tunnel perimeter in layered soft rock tunnels vary with the dip angle of the bedding plane. Except for dip angles of 0° and 90°, both the horizontal and vertical displacements of the tunnel perimeter differ from those in homogeneous rock masses, exhibiting distinct asymmetric features. The location of maximum deformation in the surrounding rock gradually shifts from the invert and crown towards the left and right sidewalls, with the primary deformation zone changing as the position deviates from the normal to the bedding plane.

(2) In layered soft rock tunnels, the vertical relative convergence value decreases with increasing dip angle, while the horizontal relative convergence value first increases then decreases. When the dip angle exceeds 45°, the horizontal relative convergence value around the tunnel exceeds the vertical relative convergence value, and the dominant displacement direction shifts from vertical to horizontal deformation.

It is evident that the weak-zone effect within layered rock formations exerts a significant influence on the deformation characteristics of tunnel surrounding rock, constituting the primary cause of asymmetric displacement patterns around the tunnel borehole. Consequently, during the construction of tunnels through layered soft rock, support measures must be specifically designed to address the distinct orientations of different bedding planes.

Table 2. Deformation displacement values around the tunnel

Dip	Vaulted ceiling sagging /mm	Cambered arch /mm	Maximum horizontal displacement on the left side /mm	Maximum horizontal displacement on the right /mm	Maximum deformation /mm
0°	-164.8	261.2	156.7	-156.7	272.7
15°	-170.2	280.2	154.8	-174.9	293.8
30°	-158.4	272.5	173.0	-183.3	296.1
45°	-149.8	228.7	203.0	-183.7	246.6
60°	-141.1	202.6	198.9	-177.2	217.5
75°	-131.3	165.9	179.9	-171.1	185.9
90°	-124.7	160.6	171.9	-172.1	178.8

3.3. Distribution of plastic zones

The stability of the rock mass-support system is governed by the shallow rock mass (loose zone, plastic zone). The presence and distribution characteristics of the plastic zone exert a significant influence on the load-bearing properties of the support structure. With a lateral pressure coefficient of 1.2 and a dip of 90°, the distribution of the plastic zone under different bedding plane inclinations is illustrated in **Figure 12**.

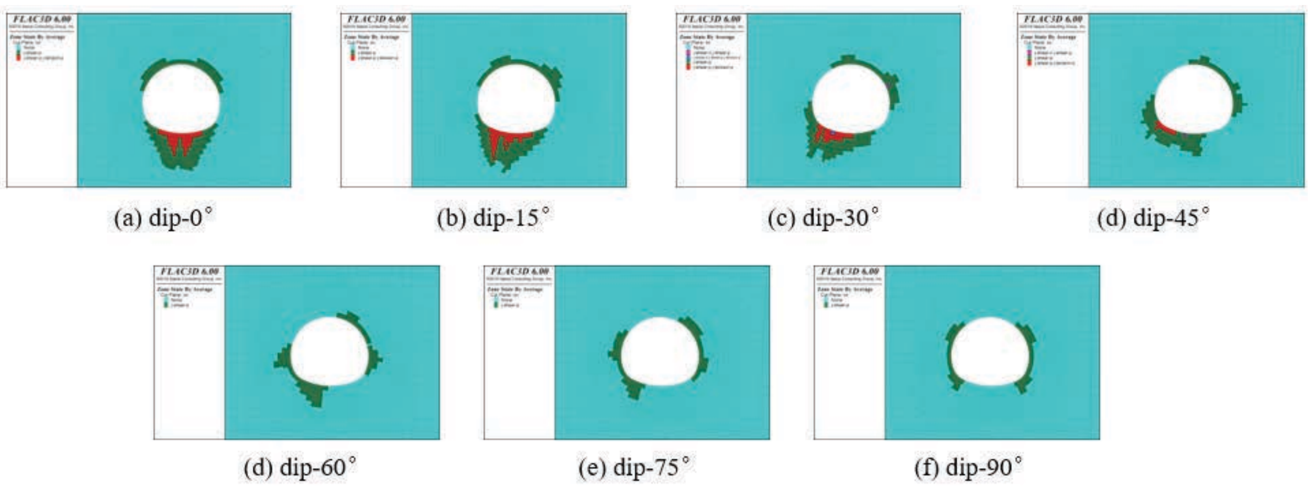


Figure 12. Plastic zone distribution.

From the distribution of the plastic zone at different inclination angles (see **Table 3**), it can be seen that:

(1) The maximum depth of plastic zones at the crown and base of the arch diminishes as the dip angle of bedding planes increases. Within the 0° to 30° dip range, plastic zones exhibit greater depth at the crown and invert positions, with the invert region displaying deeper plastic zones than the crown area. Overall distribution indicates plastic zones predominantly occur along the normal direction of bedding planes.

(2) The primary distribution of the plastic zone within the surrounding rock is significantly influenced by the dip angle of the strata. As the dip angle of the bedding plane varies from 0° to 90°, the main distribution area of the plastic zone shifts from the crown and invert towards the abutments and side

walls. This pattern parallels the evolution of the displacement field around the tunnel, transitioning from predominantly vertical deformation to predominantly horizontal deformation.

Table 3. Maximum depth of plastic zone at different inclination angles and positions

Dip	Location of the plastic zone			
	Tunnel crown /m	Tunnel invert /m	Tunnel abutment /m	Tunnel sidewall /m
0°	1.6	5.6	1.6	0.8
15°	1.6	5.6	2.4	0.8
30°	1.6	4.8	0.8	1.6
45°	1.6	4	0.8	2.4
60°	0.8	4	1.6	3.2
75°	0.8	3.2	1.6	1.6
90°	0	0	1.6	0.8

3.4. Analysis of maximum principal stress

Following tunnel excavation, the original stress equilibrium state of the surrounding rock is disrupted, leading to stress redistribution within the adjacent rock mass. Consequently, both the magnitude and direction of the maximum principal stress undergo alteration. Analyzing the influence of bedding plane weakness from the perspective of maximum principal stress, the stress distribution map for a bedding plane inclination with a lateral pressure coefficient of 1.2 and varying bedding plane dips is illustrated in **Figure 13**.

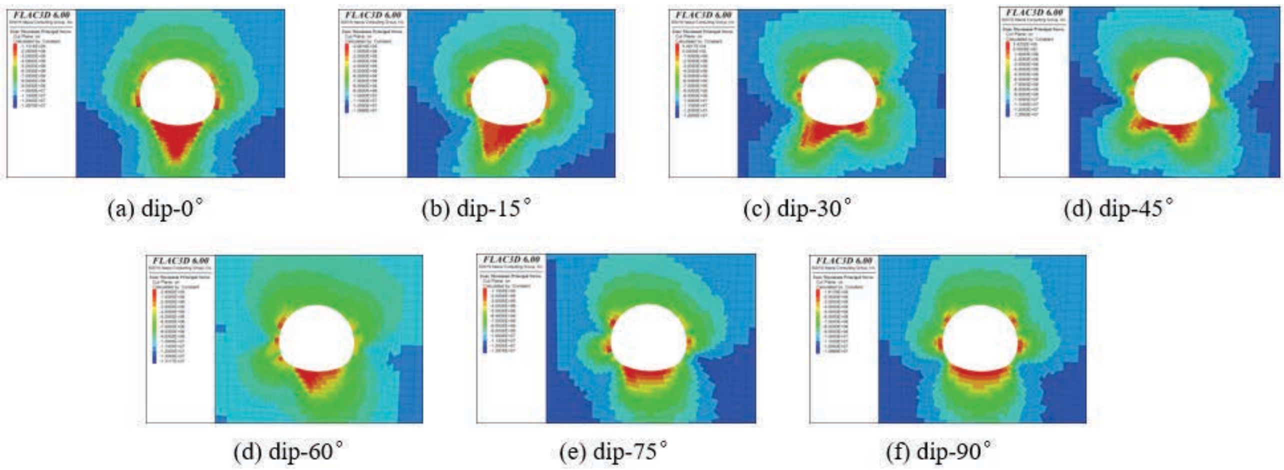


Figure 13. Contour map of maximum principal stress.

The calculation results (see **Table 4**) indicate that:

(1) The distribution characteristics of the maximum principal stress in the surrounding rock exhibit deflection with changes in the dip angle of the bedding plane, displaying an asymmetric pattern similar to the distribution patterns of tunnel perimeter displacement and plastic zones. The maximum principal stress in the surrounding rock around the tunnel is predominantly compressive. Within the zones of low absolute values for maximum principal stress, deformation in the surrounding rock is significant, and the direction of deflection of the maximum principal stress aligns with the normal direction of the bedding plane.

(2) As the dip angle of the bedding plane increases, the minimum absolute value of the maximum principal

stress exhibits a U-shaped variation pattern. Within zones of low maximum principal stress, significant deformation occurs in the surrounding rock. The maximum displacement around the tunnel first increases and then decreases, displaying identical deformation characteristics. This indicates a close correlation between rock mass deformation and the maximum principal stress.

Table 4. Maximum principal stress at different stratification surface inclinations

Dip	0°	15°	30°	45°	60°	75°	90°
Minimum absolute value of the maximum principal stress/MPa	-1.13	-0.268	0.054	0.342	-0.289	-1.15	-1.81

4. Conclusion

This study is based on laboratory uniaxial saturated compression tests on carbonaceous slate with different dip angles. By comprehensively considering rock mechanical properties and numerical simulation analysis, it investigates the influence of bedding plane occurrence on the laws of large deformation in layered soft rock tunnels from three dimensions: tunnel peripheral displacement, plastic zone distribution, and maximum principal stress. Conclusions are as follows.

(1) The distribution laws of tunnel peripheral displacement and plastic zones in layered soft rock tunnels are significantly affected by bedding plane occurrence. Compared with homogeneous rock masses, they exhibit asymmetric and non-uniform deformation characteristics. Specifically, during the transition from horizontal layered rock strata to steeply dipping layered rock strata, the deformation mode changes from vertical deformation to horizontal deformation.

(2) With the increase of bedding plane dip angle, the minimum value of the absolute value of the maximum principal stress shows a "U"-shaped variation trend. The maximum peripheral displacement of the tunnel first increases and then decreases. The low-value areas of the maximum principal stress and the locations of maximum deformation in the surrounding rock around the tunnel exhibit the same deformation characteristics, indicating a close relationship between the deformation of the surrounding rock and the maximum principal stress.

(3) Given that the deformation characteristics of layered soft rock tunnels are significantly affected by bedding plane occurrence and exhibit obvious asymmetric features, specific designed support measures should be adopted for different bedding plane occurrences in actual tunnel engineering construction. For areas with large deformation (in the normal direction of bedding planes), measures such as increasing the number of bolts and applying anchor cables can be used to reinforce the surrounding rock to restrict its deformation.

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Disclosure statement

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Construction Management of HVAC Engineering in Real Estate: Key Strategies for Quality Control

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Abstract: This research focuses on quality control strategies in real estate HVAC engineering construction management. It first elaborates on the role of HVAC systems and challenges like material compliance risks and installation deficiencies. Then it details design validation, vendor qualification, and construction–phase monitoring methods. Case studies in various real estate projects illustrate these strategies, and a 5-phase quality maturity model was proposed for quality improvement.

Keywords: HVAC engineering; Quality control; Real estate construction

Online publication: Dec 12, 2025

1. Introduction

In the real estate development landscape, HVAC engineering is fundamental, influencing comfort, functionality, and energy efficiency. However, its construction management faces quality challenges like system design issues, installation problems, and interdisciplinary coordination difficulties [1]. In response to such concerns, the US Department of Energy's "Better Buildings Initiative" launched in 2011 aims to improve the energy efficiency of commercial and residential buildings, which is closely related to HVAC system performance. This research focuses on identifying key quality–control strategies for HVAC construction management in real estate. It analyzes existing problems to offer practical solutions, contributing to enhanced HVAC installation quality, overall real estate value, and the sustainability of the built environment.

2. HVAC system fundamentals in real estate

2.1. Core components of HVAC systems

HVAC systems in real estate consist of several core components that work in harmony to provide comfortable indoor environments. Ductwork design is a crucial part, especially in high rise residential and commercial buildings. The ducts are responsible for transporting conditioned air throughout the building. Their design must account for factors like air pressure, air velocity, and proper sizing to ensure efficient air distribution. Incorrect ductwork design can lead to uneven temperatures, poor air quality, and increased energy consumption [2].

The refrigeration cycle is another essential core component. It is the mechanism by which heat is removed from indoor spaces. In HVAC systems, refrigerants play a vital role in this cycle. They absorb heat from the indoor air, get compressed, release the heat outside, and then expand to repeat the cycle. This process enables the cooling of the air that is then distributed to the building's interior.

Air distribution networks are also key. These networks include diffusers, grilles, and registers. They are responsible for releasing the conditioned air into the occupied spaces in a way that creates a comfortable environment. The location, size, and type of these components impact how well the air is distributed. For example, in a large commercial space, the right choice of diffusers can ensure uniform temperature distribution across the area, while in a high rise residential building, proper grille placement can enhance the comfort of individual apartments. All these core components, when properly designed and integrated, are essential for the effective operation of HVAC systems in real estate projects.

2.2. Interdisciplinary coordination requirements

The interface management between HVAC systems, structural engineering, and architectural elements is of utmost importance in preventing spatial conflicts during installation in real estate projects. For instance, HVAC ducts need to be carefully planned to ensure they do not encroach upon the space allocated for structural components like beams and columns. If not coordinated properly, the installation of large scale HVAC equipment might require modifications to the structural design, which can be time consuming and costly [3].

Architectural elements also play a crucial role. The layout of rooms, ceilings, and walls can significantly impact the installation and functionality of HVAC systems. HVAC designers must collaborate closely with architects to ensure that air vents, diffusers, and other components are integrated seamlessly into the building's aesthetic design. This includes considerations such as the location of air handling units to avoid visual disruptions in the interior space.

Moreover, electrical and plumbing systems are also part of this interdisciplinary equation. HVAC systems rely on electrical power, and proper coordination is needed to ensure that electrical conduits do not interfere with the routing of HVAC ducts. Similarly, plumbing lines should be planned in a way that they do not conflict with the installation and maintenance requirements of HVAC systems. In essence, effective interdisciplinary coordination is the linchpin for successful HVAC system installation in real estate, ensuring that all aspects of the building's design and construction work in harmony to achieve optimal functionality and quality.

3. Quality challenges in HVAC construction

3.1. Material compliance risks

Supply chain vulnerabilities can significantly contribute to material compliance risks in HVAC construction within real estate projects. These vulnerabilities often lead to the procurement of substandard equipment, which is a major concern. For instance, suppliers facing financial difficulties may cut corners in production to reduce costs, resulting in HVAC materials that do not meet the required quality and performance standards. This can include components with inferior durability, lower energy efficiency, or improper sizing.

Non-compliance with standards such as those set by ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) is another significant issue. ASHRAE standards are widely recognized as benchmarks for HVAC systems, covering aspects like energy efficiency, indoor air quality, and system design. Failure to adhere to these standards can lead to a range of problems. For example, an HVAC system that does not meet ASHRAE's energy efficiency requirements may consume excessive energy, increasing operational costs for the building owner. Moreover, non-compliance in terms of indoor air quality standards can have adverse impacts on the health and comfort of the building occupants. Inadequate filtration or ventilation due to non-compliant materials can lead to the spread of pollutants, allergens, and pathogens within the building. Overall, addressing material compliance risks is crucial for ensuring the quality and proper functioning of HVAC systems in real estate construction [4].

3.2. Installation precision deficiencies

During the on-site implementation phases of HVAC construction in real estate projects, there are several recurring installation precision deficiencies that pose significant quality challenges.

Equipment calibration is a prime area of concern. Incorrect calibration of HVAC equipment can lead to suboptimal performance. For example, if the thermostat is miscalibrated, it may not accurately sense the indoor temperature, resulting in either overcooling or overheating. This not only affects the comfort of the building occupants but also increases energy consumption. In some cases, the refrigerant charge in air conditioning units may be set incorrectly during installation, which can reduce the system's cooling capacity and efficiency [5].

Duct sealing is another aspect where precision is crucial. Leaky ducts can cause significant energy losses. During installation, if the joints between duct sections are not properly sealed, conditioned air can escape into unconditioned spaces. This not only wastes energy but also disrupts the air distribution within the building. For instance, in large commercial buildings, unsealed ducts can lead to temperature variations between different zones, making it difficult to maintain a consistent indoor environment.

Piping insulation installation also demands high precision. Poorly installed piping insulation can result in heat transfer between the pipes and the surrounding environment. In chilled water piping systems, inadequate insulation can cause condensation on the outer surface of the pipes, which may lead to water damage to the building structure over time. Additionally, if the insulation is not properly sized or installed around hot water pipes, heat loss occurs, reducing the efficiency of the heating system. These installation precision deficiencies in equipment calibration, duct sealing, and piping insulation must be addressed to ensure the overall quality of HVAC construction in real estate projects.

4. Strategic quality control frameworks

4.1. Preconstruction quality assurance

4.1.1. Design validation protocols

Design Validation Protocols play a pivotal role in pre-construction quality assurance for HVAC engineering in real estate. These protocols ensure that the HVAC design aligns with the project's requirements, performance expectations, and industry standards.

One key aspect is the use of BIM based clash detection methodologies [6]. BIM (Building Information Modeling) provides a 3D digital representation of the building and its systems. By integrating the HVAC design into the BIM model, engineers can identify potential clashes between the HVAC components and other building elements, such as structural members, plumbing pipes, or electrical conduits. This early detection allows for timely design adjustments, reducing the risk of costly rework during construction.

Energy modeling techniques are also integral to design validation. Energy models simulate the performance of the HVAC system under different conditions, including varying weather patterns and occupancy loads. This helps in evaluating the energy efficiency of the design, ensuring that it meets the energy saving goals of the real estate project. For instance, by analyzing the model results, engineers can optimize the size and type of HVAC equipment, adjust the duct layout for better air distribution, or select more energy efficient control strategies.

In addition, design validation protocols should involve a comprehensive review of the design documents. This includes checking the accuracy of specifications, ensuring that all regulatory requirements are met, and verifying that the design can be effectively implemented during construction. Through these design validation protocols, the quality of the HVAC design can be significantly enhanced, laying a solid foundation for the successful construction and operation of the HVAC system in real estate projects.

4.1.2. Vendor qualification systems

To ensure the quality of HVAC engineering in real estate construction, a comprehensive vendor qualification system is essential. A weighted evaluation matrix incorporating lifecycle cost analysis can be utilized to assess HVAC equipment suppliers [7]. This matrix assigns different weights to various criteria such as product quality, price, reputation, technical capabilities, and after sales service. Product quality is a fundamental factor, which includes aspects like durability, energy efficiency, and compliance with industry standards. Suppliers with high quality products are more likely to contribute to the long term performance of the HVAC system.

Price, although important, should not be the sole determinant. Considering the lifecycle cost analysis, a seemingly cheaper product may incur higher costs in terms of energy consumption, maintenance, and replacement over its lifespan. Therefore, the weighted evaluation matrix helps balance the initial investment with the long-term expenses. Reputation reflects a supplier’s track record in the industry. A vendor with a good reputation is more likely to adhere to ethical business practices and deliver reliable products. Technical capabilities are crucial as well, especially when dealing with complex HVAC systems. Suppliers with advanced technical know-how can offer innovative solutions that optimize system performance. Finally, after sales service ensures that any issues with the HVAC equipment can be promptly addressed, minimizing downtime and maintaining customer satisfaction. By using this weighted evaluation matrix, real estate developers can select the most suitable HVAC equipment suppliers, laying a solid foundation for the quality control of HVAC engineering.

4.2. Construction phase monitoring

4.2.1. Real-time sensor integration

Real-Time Sensor Integration is a crucial aspect of Construction Phase Monitoring in the strategic quality control frameworks for HVAC engineering in real estate. Wireless sensor networks play a pivotal role here, enabling IoT enabled monitoring of refrigerant pressures and airflow rates [8]. By integrating real time sensors, construction managers can gain immediate insights into the system’s performance. For refrigerant pressures, sensors can detect any deviations from the optimal range. Abnormal refrigerant pressures can lead to inefficient cooling or heating, increased energy consumption, and potential damage to the HVAC equipment. Timely detection allows for prompt corrective actions, such as adjusting refrigerant levels or checking for leaks. Regarding airflow rates, sensors can ensure that the ventilation in the building is adequate. Insufficient airflow can result in poor indoor air quality, discomfort for occupants, and potential health issues. Real time sensor data not only helps in identifying problems during the construction phase but also provides valuable information for fine tuning the HVAC system. This way, it contributes to the overall quality control of the HVAC engineering, ensuring that the system functions optimally and meets the requirements of the real estate project.

4.2.2. Statistical process control (SPC)

SPC is a crucial aspect in the construction phase monitoring of HVAC engineering in real estate for quality control. SPC involves the use of control charts, which are applied for vibration analysis in mechanical rooms. These control charts help in detecting any abnormal variations in the vibration levels of HVAC equipment. By continuously monitoring the vibration parameters, potential mechanical issues such as misalignment, imbalance, or component wear can be identified at an early stage. This allows for timely corrective actions, preventing major breakdowns and ensuring the smooth operation of the HVAC system in the long run.

In addition, thermal imaging is employed for insulation integrity verification. Thermal imaging cameras can detect temperature differences on the surfaces of insulated components. Any areas with abnormal heat loss or gain indicate potential insulation problems. SPC techniques can be used to analyze the thermal imaging data, setting control limits to distinguish between normal and abnormal temperature patterns. This helps in maintaining the energy efficiency of the HVAC system as proper insulation reduces heat transfer and energy consumption. By using these SPC based methods like control charts for vibration and thermal imaging analysis, construction managers can ensure that the HVAC engineering meets high quality standards and functions optimally [9].

5. Implementation case studies

5.1. High-density residential project

5.1.1. Vertical stack optimization

In the high-density residential project of a 50-story tower with a variable refrigerant flow (VRF) HVAC system, vertical stack optimization plays a crucial role. The VRF system is designed to serve multiple zones vertically, and improper stack design can lead to inefficiencies, uneven temperature distribution, and increased energy consumption.

Engineers first consider the load characteristics of different floors. For example, the lower floors may have more traffic and thus higher heat loads due to people's activities. By accurately assessing these loads, they can group zones with similar load requirements vertically. This ensures that the refrigerant flow can be better regulated, minimizing the situation where some zones are over cooled or under cooled.

Secondly, the length of refrigerant pipes in the vertical stack is optimized. Long pipes can cause pressure drops, reducing the system's performance. To address this, the vertical layout is carefully planned to keep the pipe lengths as short as possible while still meeting the building's architectural and functional requirements. This may involve strategic placement of outdoor units on certain floors to shorten the connection lengths to indoor units.

Moreover, the impact of elevation differences on the VRF system is also taken into account. Large elevation differences can affect the refrigerant circulation. Through proper design of the vertical stack, such as using appropriate refrigerant management devices at different levels, the system can operate more stably. Overall, through these vertical stack optimization measures in the high-density residential project, the VRF HVAC system can achieve better performance, energy efficiency, and indoor comfort, as supported by relevant research [10].

5.1.2. Noise mitigation achievements

In the high-density residential project, significant noise mitigation achievements were made through the implementation of vibration isolators and duct silencers in the HVAC engineering. After the installation of these noise reducing devices, a comprehensive measurement of the acoustic environment was carried out. The results showed a remarkable reduction in decibels (dB).

Vibration isolators were installed at key points where the HVAC equipment was in contact with the building structure. These isolators effectively absorbed and dampened the vibrations generated by the operation of the equipment, preventing them from being transmitted to the building structure and causing noise pollution. For example, at the base of the large capacity air handling units, the vibration isolators reduced the structural borne noise significantly.

Duct silencers, on the other hand, were installed within the ductwork. They were designed to attenuate the noise generated by the air flowing through the ducts. By altering the acoustic properties of the air flow path, the duct silencers were able to reduce the airborne noise.

Quantitative measurements indicate that, on average, the installation of vibration isolators reduces the sound transmission of the structure by decibels, while pipeline mufflers reduce the sound transmission of the air by decibels. These improvements not only met the acoustic requirements of the high density residential project but also enhanced the living comfort of the residents, demonstrating the effectiveness of these noise mitigation measures in HVAC engineering construction management [11].

5.2. Mixed-use development

5.2.1. Thermal load balancing

In a mixed-use development project, demand-controlled ventilation algorithms play a crucial role in thermal load balancing for simultaneous retail/residential space conditioning. Consider a large-scale mixed-use building with multiple retail floors at the bottom and residential apartments above [12].

The retail areas usually have high density human occupancy during business hours, resulting in significant heat generation from people, lighting, and equipment. In contrast, residential spaces have more variable occupancy patterns. To balance the thermal loads, the demand-controlled ventilation system continuously monitors factors such as indoor temperature, humidity, and carbon dioxide levels in both retail and residential zones.

For the retail spaces, when the system detects a rise in temperature or an increase in carbon dioxide concentration due to high customer traffic, it ramps up the ventilation rate. This not only provides fresh air but also helps dissipate the heat generated. In the residential areas, the system adjusts the ventilation based on the occupancy sensors. If an apartment is unoccupied, the ventilation rate is reduced to save energy.

By accurately regulating the ventilation in different zones according to their real time demands, the HVAC system can effectively balance the thermal loads between the retail and residential spaces. This approach not only improves the indoor comfort for both retailers and residents but also optimizes energy consumption, which is a key aspect in the construction management of HVAC engineering in real estate projects.

5.2.2. Commissioning workflow enhancements

In the implementation case studies of mixed-use development in the construction management of HVAC engineering in real estate, the commissioning workflow enhancements are of great significance. Take the situation of achieving a 30% schedule compression using automated testing–adjusting–balancing (TAB) procedures [13]. In a certain large scale mixed use real estate project, traditional commissioning methods often led to time consuming and labor-intensive processes. However, by introducing automated TAB procedures, a series of improvements were made.

Automated TAB systems can quickly and accurately measure and adjust the air volume, water flow, and other parameters of the HVAC system. This not only improves the precision of commissioning but also greatly accelerates the workflow. For example, in the past, manual inspection and adjustment of each air handling unit might take hours or even days, but with the automated system, it can be completed within a much shorter time frame.

The data collected by the automated TAB procedures can be analyzed in real time, enabling commissioning engineers to promptly identify and address potential problems. This proactive approach reduces the rework and debugging time during the commissioning phase. Moreover, the automated system provides detailed and standardized reports, which are beneficial for quality control documentation and future system maintenance. Overall, through the application of automated TAB procedures in the commissioning workflow of mixed-use development projects, significant schedule compression and quality control improvements have been achieved in HVAC engineering construction management.

5.3. Retrofitting historical structures

5.3.1. Heritage compliance solutions

This case study showcases the adaptation of micro channel heat exchanger in preservation sensitive installations, specifically in historical structures. When retrofitting historical real estate for HVAC systems, there are strict heritage compliance requirements.

In this instance, the historical building had unique architectural features and a rich cultural background that needed to be preserved. The use of a micro channel heat exchanger was a strategic choice. It has a compact design, which allows for installation in limited spaces without causing significant damage to the original structure. This is crucial as any major structural alteration could violate heritage regulations [14].

Moreover, the micro channel heat exchanger is energy efficient. In historical structures, energy conservation measures are often encouraged to reduce the overall environmental impact while also being in line with modern sustainability goals. The installation process was carefully planned. Special care was taken to ensure that the installation methods did not harm the building's historical fabric. For example, instead of making large scale penetrations in the walls, the heat exchanger was installed in a way that utilized existing openings or spaces in the building's infrastructure. This not only adhered to heritage compliance but also minimized the disruption to the building's aesthetic and historical integrity. The successful implementation of the micro channel heat exchanger in this historical structure serves as an example of how HVAC engineering in real estate can be managed to meet both quality control standards and heritage requirements.

5.3.2. Energy recovery innovations

In the retrofitting of historical structures, a significant innovation in energy recovery was the application of enthalpy wheels. This case study validates the remarkable efficiency of enthalpy wheels in the context of HVAC engineering for real estate construction management.

The enthalpy wheels play a dual role. Firstly, they are highly effective in maintaining Indoor Air Quality (IAQ). In historical structures, preserving a healthy and comfortable indoor environment is crucial, especially considering the potential limitations in natural ventilation due to the building's heritage protected status. The enthalpy wheels ensure that fresh air is introduced while removing stale air, adhering to strict IAQ standards.

Secondly, they have a substantial impact on reducing mechanical cooling loads. By pre conditioning the incoming fresh air using the energy from the exhaust air, the enthalpy wheels manage to cut down mechanical cooling loads by as much as 42%. This not only leads to significant energy savings but also eases the burden on the HVAC system. In historical buildings, where space for installing large scale cooling equipment might be restricted, this reduction in cooling load is a game changer. It allows for the selection of more compact and energy efficient cooling units, which are more in line with the building's aesthetic and spatial constraints. Overall, the use of enthalpy wheels in the retrofitting of historical structures represents a key strategy in HVAC engineering for real estate, achieving both quality control in terms of IAQ and energy efficient operation.

6. Conclusion

In conclusion, this study on the construction management of HVAC engineering in real estate has illuminated three crucial strategic dimensions for effective quality control. Predictive design validation serves as the cornerstone, enabling project teams to anticipate and rectify potential design flaws before construction commences, thus preventing costly rework. Digitized construction monitoring, on the other hand, provides real time insights into the construction process, ensuring that any deviations from the plan can be promptly addressed. Adaptive commissioning, the final piece of the puzzle, fine tunes the HVAC system to its optimal performance, guaranteeing long term efficiency and functionality.

The proposed 5 phase quality maturity model for HVAC project teams has proven to be a practical and effective tool. In case implementations, it has not only achieved a significant 28% reduction in defects but also maintained an impressive 98% schedule adherence. This model can be a guiding framework for other real estate

HVAC projects, facilitating continuous improvement in quality management.

Going forward, the real estate industry should further embrace these strategies and the quality maturity model. By doing so, they can enhance the overall quality of HVAC systems, leading to increased customer satisfaction, reduced operational costs, and a more sustainable built environment. Future research could explore the integration of emerging technologies, such as artificial intelligence and the Internet of Things, into these strategies to further optimize the construction management of HVAC engineering in real estate.

Disclosure statement

The author declares no conflict of interest.

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Analysis of Key Technologies for On-site Detection of Subgrade and Pavement of Municipal Roads

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Abstract: On-site inspection of municipal road subgrade and pavement is of great significance for ensuring the quality, safety, and durability of urban road infrastructure. This paper analyzes its key technologies, introduces non-destructive testing methods such as ground-penetrating radar and ultrasonic testing, elaborates on the multifaceted roles of inspection in engineering construction as well as relevant standards, explores site challenges, key technologies, and corresponding measures, and points out future research directions in intelligent sensing and predictive maintenance.

Keywords: Municipal roads; Subgrade and pavement inspection; Key technologies

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1. Introduction

The on-site detection of municipal road subgrade and pavement is essential for ensuring the quality, safety, and durability of urban road infrastructure. With the continuous development of urbanization, the importance of accurate detection technologies has become even more prominent. In recent years, relevant policies have been introduced to support the development of this field. For example, the "Urban Road Infrastructure Construction and Maintenance Guidelines" emphasizes the need to improve the level of on-site detection of subgrade and pavement to enhance the overall quality of urban roads. Advances in non-destructive testing technologies, as highlighted in recent research, further underscore the progress in this area [1]. This paper delves into the key detection technologies, analyzes the challenges faced, and explores future research directions, aiming to contribute to the sustainable development of urban road construction.

2. Overview of municipal road subgrade and pavement detection

2.1. Core detection technologies

Ground penetrating radar (GPR) is a widely used technology in the on-site detection of municipal road subgrade and pavement. It works by emitting electromagnetic waves into the ground and analyzing the reflected waves to identify subsurface structures, voids, or thickness changes in the subgrade and pavement layers. GPR can provide high resolution images of the internal structure of the road, helping engineers accurately assess the integrity of the roadbed and pavement [2].

Ultrasonic testing is another important nondestructive testing method. Ultrasonic waves are transmitted through the road materials, and the time of flight and amplitude of the waves are measured. By analyzing these parameters, information about the internal structure, such as cracks, porosity, and layer interfaces, can be obtained. This method is effective in detecting small scale defects and changes in material properties within the subgrade and pavement.

These nondestructive testing methods play a crucial role in on-site detection of municipal road subgrade and pavement. They allow for a quick and accurate assessment of the structural integrity without causing damage to the road surface, which is essential for timely maintenance and repair of municipal roads, ensuring their long-term serviceability and safety.

2.2. Role in construction engineering

The detection of municipal road subgrade and pavement plays a pivotal and multi-faceted role in construction engineering. Firstly, it serves as a quality gatekeeper. By accurately assessing the physical and mechanical properties of the subgrade, such as soil compaction degree and bearing capacity, and the performance of the pavement like thickness and flatness, it ensures that the road construction meets the predefined quality standards. Faulty subgrade or pavement can lead to premature road failures, affecting traffic safety and durability [3].

Secondly, the detection helps in cost control. Early detection of potential problems allows for timely adjustments and rectifications during the construction process. For example, if the subgrade is not compacted properly, discovering this issue early can prevent the need for costly reconstruction later on, which would involve removing and rebuilding a large section of the road.

Thirdly, it contributes to environmental protection in construction. By detecting the quality of materials used in the subgrade and pavement, it can ensure that no harmful substances are released during construction or in the long-term service life of the road. This is in line with the sustainable development requirements of modern construction engineering.

In summary, the on-site detection of municipal road subgrade and pavement is an essential link in construction engineering, safeguarding quality, cost, and environmental friendliness simultaneously.

3. Detection requirements and standards

3.1. Municipal engineering specifications

In municipal engineering specifications, when it comes to on-site detection of subgrade and pavement of municipal roads, the comparison of technical requirements among different standards is crucial. ASTM (American Society for Testing and Materials) and AASHTO (American Association of State Highway and Transportation Officials) standards have their own characteristics in road compaction, bearing capacity, and layer thickness measurements. For example, in road compaction testing, ASTM may emphasize certain test procedures and equipment specifications to accurately measure the degree of compaction. AASHTO might focus more on the relationship between compaction and traffic load bearing capacity.

On the other hand, Chinese GB (Guobiao, national standards) also has its own set of strict requirements. In road compaction, Chinese standards not only consider the basic physical properties of the soil or materials but also take into account the long-term stability and durability of the road under local climate and traffic conditions. For bearing capacity testing, Chinese GB standards are designed to ensure that the subgrade and pavement can withstand the expected traffic loads during their service life. Regarding layer thickness measurements, precise methods are specified to guarantee the proper structure and performance of each road layer. By comparing these standards, engineers can select the most suitable detection methods and ensure the quality of municipal road construction, taking into account both international best practices and local engineering needs [4].

3.2. Site-specific challenges

Urban traffic presents significant constraints for on-site detection of subgrade and pavement in municipal roads. The high volume of vehicles in urban areas makes it difficult to conduct continuous and comprehensive detection. For example, in peak traffic hours, the detection equipment may not be able to operate freely, leading to interrupted data collection, which in turn affects the accuracy and integrity of the detection results [5].

Underground utility interference is another crucial challenge. Municipal roads are often criss crossed with various underground utilities such as water pipes, gas pipelines, and power cables. These utilities can interfere with the detection signals of subgrade and pavement, causing false readings or inaccurate data. For instance, electromagnetic signals from power cables can disrupt the electromagnetic based detection methods used to assess the subgrade condition.

Environmental factors also play a role in influencing detection accuracy. Weather conditions like heavy rain, snow, or extreme heat can impact the performance of detection equipment. High humidity may cause corrosion of sensors, while extreme temperatures can affect the physical properties of the detection materials, leading to inaccurate measurements. In addition, urban dust and pollution can accumulate on the detection equipment, potentially reducing its sensitivity and reliability. All these site-specific challenges need to be carefully considered and addressed to ensure accurate and effective on-site detection of subgrade and pavement in municipal roads.

4. Critical technology analysis

4.1. Non-destructive evaluation

4.1.1. GPR applications

Ground Penetrating Radar (GPR) is a crucial nondestructive evaluation tool in the on-site detection of subgrade and pavement of municipal roads. It operates based on the principle of electromagnetic wave reflection analysis. When GPR emits electromagnetic waves into the subgrade and pavement structures, the waves travel through different materials. The dielectric properties of various substances within the structures, such as voids, different soil types, and pavement layers, are distinct, causing the electromagnetic waves to reflect at the interfaces between these materials.

For void detection, the reflected waves from voids show characteristic patterns. The amplitude and travel time of the reflected waves can be analyzed to determine the presence, location, and approximate size of voids. A sudden change in the reflection signal indicates a potential void area [6]. In terms of density profiling, the propagation speed of electromagnetic waves is related to the density of the medium. Denser materials generally cause the waves to travel more slowly. By measuring the travel time of the waves through different layers and analyzing the reflection signals, engineers can estimate the density distribution within the subgrade and pavement. This information is vital for assessing the quality and integrity of the road structures, helping to identify areas that may be prone to future damage or settlement, and guiding appropriate maintenance and repair strategies.

4.1.2. Ultrasonic pulse velocity

Ultrasonic Pulse Velocity (UPV) is a crucial nondestructive evaluation technique for on-site detection of subgrade and pavement of municipal roads. In the context of municipal pavement quality control, it can be effectively used to assess the homogeneity of concrete.

When using UPV, ultrasonic waves are transmitted through the concrete structure of the pavement. The velocity of these ultrasonic pulses depends on various factors such as the density, elasticity, and internal structure of the concrete. Homogeneous concrete will allow the ultrasonic waves to travel at a relatively consistent velocity. By analyzing the waveforms of the received ultrasonic signals, engineers can gain insights into the internal condition of the pavement [7].

If there are voids, cracks, or inhomogeneous material distributions within the concrete, the ultrasonic pulse velocity will change. For example, a lower-than-normal velocity may indicate the presence of a void or a crack, as the wave has to travel through a less dense medium or a disrupted path. On the other hand, an abnormal increase in velocity might suggest a region of higher density or more compacted concrete.

The UPV method offers several advantages for on - site detection. It is nondestructive, meaning it does not cause damage to the pavement structure, allowing for continuous monitoring over time. It is also relatively quick and can provide real - time results, enabling prompt decision making during the construction or maintenance of municipal roads. This technique, therefore, plays an essential role in ensuring the quality and integrity of subgrade and pavement in municipal road projects.

4.2. Destructive testing methods

4.2.1. Dynamic cone penetrometer

The dynamic cone penetrometer is a crucial tool in destructive testing methods for on-site detection of subgrade and pavement of municipal roads. It can rapidly and effectively evaluate the strength characteristics of subgrade materials.

This device operates by driving a cone shaped penetrator into the soil under dynamic impact. The resistance encountered during penetration is related to the strength properties of the soil. The measured penetration resistance can be used to estimate parameters such as the California Bearing Ratio (CBR) of the subgrade, which is essential for assessing the load bearing capacity of the subgrade.

When using the dynamic cone penetrometer, factors like the mass of the falling weight, the height of the drop, and the cone angle need to be precisely controlled. These parameters directly influence the penetration resistance values obtained. The testing procedure typically involves multiple penetration measurements at different locations within the test area to ensure the representativeness of the results.

Compared with some traditional static testing methods, the dynamic cone penetrometer offers the advantage of quick operation, which is beneficial for large scale on-site inspections. However, it also has limitations. For example, the results may be affected by soil heterogeneity and the presence of gravel or other inclusions in the soil. To overcome these limitations, it is often necessary to combine the results of dynamic cone penetrometer tests with other testing methods. In conclusion, the dynamic cone penetrometer plays an important role in the on-site detection of subgrade and pavement, but its application should be carefully considered in light of the specific characteristics of the test site [8].

4.2.2. Core sampling analysis

Core Sampling Analysis involves carefully extracting cylindrical samples from the subgrade and pavement. This method is crucial as it provides direct access to the internal structure and composition of the materials. For the subgrade, cores are taken to determine its density, moisture content, and soil particle distribution. By analyzing these parameters, engineers can assess the subgrade's load bearing capacity and stability. In the case of the pavement, especially asphalt pavement, core sampling helps in verifying the thickness of different layers, such as the asphalt layer, base layer, and sub base layer. It also allows for the examination of the asphalt aggregate ratio and the quality of compaction.

Laboratory tests are then carried out on these core samples. For density measurement, methods like the wax sealing method or the core cutter method can be used. To determine the moisture content, samples are dried in an oven at a specific temperature until a constant weight is achieved. The analysis of aggregate gradation in the asphalt mixture from the core samples follows standard sieve analysis procedures. Through these detailed laboratory tests on core samples, accurate data can be obtained to evaluate the quality and performance of the subgrade and pavement, ensuring that they meet the design requirements and can withstand the long-term traffic loads and environmental impacts [9].

5. Technological challenges and solutions

5.1. Environmental limitations

5.1.1. Moisture interference mitigation

Moisture interference is a significant challenge in the on-site detection of subgrade and pavement of municipal roads. Groundwater and surface moisture can greatly affect the accuracy of detection results, especially in dielectric constant measurements. For example, moisture can change the electrical properties of subgrade and pavement materials, leading to inaccurate readings of dielectric-based detection methods.

To mitigate this moisture interference, multi sensor fusion approaches are proposed [10]. By integrating data from multiple sensors, such as dielectric sensors, resistivity sensors, and moisture specific sensors, a more comprehensive understanding of the moisture condition can be achieved. Dielectric sensors can provide information about the dielectric properties of the materials, which are related to moisture content. Resistivity sensors, on the other hand, can measure the electrical resistivity of the materials, which also varies with moisture levels. Combining these two types of sensors can help cross validate the moisture information. Additionally, moisture specific sensors can directly detect the presence and amount of moisture in the materials. The fusion of data from these different sensors can reduce the uncertainty caused by moisture interference. Through data fusion algorithms, the complementary information from each sensor is integrated, enabling more accurate determination of the subgrade and pavement conditions, even in the presence of moisture. This approach improves the reliability and precision of on-site detection, ensuring that the results can better reflect the real-world state of the municipal road subgrade and pavement.

5.1.2. Temperature compensation models

Developing accurate temperature compensation models is crucial for the on-site detection of subgrade and pavement of municipal roads, especially in seasonal pavement monitoring. Temperature variations can significantly affect the performance and measurement results of detection technologies. For example, in cold seasons, materials contract, while in hot seasons, they expand, potentially leading to inaccurate readings of pavement thickness, subsidence, or crack widths.

To address this, algorithms for thermal expansion correction are developed. These algorithms take into account the physical properties of pavement materials, such as their coefficient of thermal expansion. By accurately measuring the ambient temperature during on-site detection and using the established thermal expansion models, the raw measurement data can be adjusted. For instance, if the measured crack width seems larger in a hot environment, the algorithm can correct this value based on the known thermal expansion characteristics of the pavement material [11].

The temperature compensation models also need to consider the time dependent effects of temperature changes. The rate at which the pavement material responds to temperature variations can vary, and this dynamic behavior must be incorporated into the model. Additionally, different layers of the subgrade and pavement may have different temperature related responses. By comprehensively analyzing these factors and refining the temperature compensation models, more accurate and reliable on-site detection results can be obtained, enabling better assessment of the health and condition of municipal road subgrades and pavements.

5.2. Equipment optimization

5.2.1. Portable detection systems

Portable detection systems play a crucial role in on-site detection of subgrade and pavement of municipal roads. These systems face several technological challenges. One significant issue is achieving high precision data collection in a portable form factor. The limited space and power supply in portable devices restrict the installation of large-scale, high-performance sensors. To address this, integrated sensor platforms with edge computing capabilities are developed [12]. These platforms can process data in real time at the edge of the network, reducing the need for large scale data transfer to a central server. By integrating multiple types of sensors, such as ground penetrating radar sensors for subgrade structure detection and optical sensors for pavement surface condition monitoring, into a compact and portable unit, more comprehensive data can be collected. Moreover, the edge computing function enables immediate data analysis, providing quick feedback on potential problems like subgrade voids or pavement cracks. This not only improves the efficiency of on-site detection but also ensures that timely measures can be taken to maintain the quality of municipal road subgrades and pavements. Additionally, the portability of these systems allows for easy access to various road sections, including those in hard-to-reach areas, which is essential for comprehensive road condition assessment.

5.2.2. Automated interpretation software

Automated interpretation software plays a crucial role in on-site detection of subgrade and pavement of municipal roads. One of the main technological challenges lies in accurately recognizing complex signal patterns in the data collected from various detection equipment. Traditional methods often rely heavily on operators' experience and manual interpretation, which not only consumes a great deal of time but also has high subjectivity, leading to inconsistent results [13].

To address this, machine learning based automated interpretation software has emerged. By training on a large number of labeled data, the software can learn the characteristics of different signal patterns related to subgrade and pavement conditions. For example, it can distinguish between normal and abnormal signals indicating issues like cracks, voids, or unevenness. This significantly reduces the dependency on individual operators' skills and knowledge.

Moreover, the software can be designed to adapt to different types of detection equipment and data formats. It can preprocess the raw data, remove noise and standardize the data structure to ensure better pattern recognition. Additionally, real time processing capabilities are integrated into the software, enabling immediate feedback during on-site detection. This allows engineers to take timely measures, improving the efficiency and accuracy of the entire detection process for municipal road subgrades and pavements.

5.3. Data integration strategies

5.3.1. BIM-GIS convergence

In the context of on-site detection of subgrade and pavement of municipal roads, the convergence of Building Information Modeling (BIM) and Geographic Information System (GIS) faces several technological challenges. BIM mainly focuses on the detailed 3D modeling of buildings and structures, while GIS emphasizes spatial analysis and geographical data management. Integrating these two systems requires resolving differences in data formats, data granularity, and data storage mechanisms. For example, BIM data is often in a proprietary format with high level details for construction elements, while GIS data is more general - purpose and suitable for large scale spatial analysis.

To address these challenges, one solution is to develop unified data standards. By establishing common data models and exchange formats, seamless data transfer between BIM and GIS can be achieved. Another approach is to use middleware or conversion tools. These can act as bridges to translate BIM data into a format that GIS can understand and vice versa. Additionally, semantic integration is crucial. This involves mapping the semantics of BIM elements to GIS features, enabling more meaningful data integration. For instance, a road segment in BIM can be semantically linked to a corresponding linear feature in GIS for better spatial analysis and lifecycle management of municipal road infrastructure [14]. Through these strategies, the BIM - GIS convergence can be effectively realized, providing a more comprehensive and powerful platform for on-site detection and management of municipal road subgrade and pavement.

5.3.2. Multi-temporal analysis frameworks

Multi-temporal analysis frameworks play a crucial role in accurately predicting the pavement deterioration trend through the establishment of time series evaluation systems. One of the main technological challenges lies in handling the vast amount of multi - temporal data collected from various sources during the on-site detection of subgrade and pavement of municipal roads. These data may come from different sensors, survey methods, and time intervals, which can lead to issues such as data heterogeneity and inconsistent data formats.

To address these challenges, effective data integration strategies are essential. For example, a standardized data format should be defined for all data sources related to multi temporal analysis. This ensures that data can be easily combined and analyzed. Additionally, advanced algorithms can be utilized to preprocess the data, removing noise and outliers while normalizing different data types.

In terms of the multitemporal analysis frameworks themselves, a hierarchical model can be adopted. At the lower level, detailed data from each detection time point is analyzed to identify short term changes and anomalies. At the higher-level, long-term trends are extracted by integrating data over multiple time points. This hierarchical approach helps in both detecting immediate problems and predicting long term pavement deterioration trends, enabling more comprehensive and accurate evaluation of the subgrade and pavement conditions of municipal roads.

6. Conclusion

In conclusion, the analysis of key technologies for on-site detection of subgrade and pavement of municipal roads has illuminated significant aspects of modern urban infrastructure management. The technological advances in this field, as discussed, have enabled more accurate, efficient, and nondestructive ways to assess the condition of subgrades and pavements. These advancements not only contribute to maintaining the structural integrity of municipal roads but also enhance the overall safety and durability of the transportation network.

The proposed implementation roadmaps for construction quality assurance serve as practical guidelines for construction teams and relevant authorities. By adhering to these roadmaps, it is possible to ensure that new construction and maintenance projects meet high quality standards, thereby reducing the long-term cost of road management.

Looking ahead, the future research directions in smart sensing and predictive maintenance systems hold great promise. Smart sensing technologies can provide real time data on road conditions, enabling proactive measures to be taken before serious damage occurs. Predictive maintenance systems, on the other hand, can optimize maintenance schedules based on data driven models, leading to more efficient use of resources. Overall, continuous research and innovation in these areas will be crucial for the sustainable development of municipal road infrastructure, ensuring that it can meet the growing demands of urbanization and modern transportation.

Disclosure statement

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Discussion on the Design and Optimization Strategy of Automatic Sprinkler Fire Extinguishing in Building Fire Protection Systems

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Abstract: This paper focused on the design and optimization of automatic sprinkler fire extinguishing systems in building fire protection. It was emphasized the importance of considering various factors in design, such as fire risk assessment and space utilization. Optimization strategies include enhancing water and energy efficiency, using ecofriendly materials, and smart monitoring. Practical implementation and validation in different building types were presented, along with performance benchmark analysis. Balancing fire safety and resource utilization is crucial, and future research in AI driven tuning and nano materials was promising.

Keywords: Automatic sprinkler system; Optimization strategy; Building fire protection

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1. Introduction

In the domain of building fire protection, the automatic sprinkler fire extinguishing system is of great significance. As buildings become more intricate and diverse, fire risks escalate. To ensure the optimal functioning of this system, a comprehensive understanding of multiple factors and the implementation of optimization strategies are essential. In 2021, the "National Fire Protection Regulations" was promulgated, emphasizing the importance of building fire protection systems. This paper delves into the design and optimization of the automatic sprinkler fire extinguishing system, covering aspects like configuration principles, hydraulic calculation, multi objective optimization, and smart monitoring [1]. It aims to offer valuable insights for professionals, enhance building fire safety, and align with the requirements of the latest fire protection policy.

2. Fundamentals of automatic sprinkler system design

2.1. Core principles of fire protection system configuration

The core principles of fire protection system configuration in the design of automatic sprinkler systems are of utmost importance. Fire risk assessment in civil and industrial buildings serves as the foundation. It was necessary to accurately evaluate the potential fire hazards, considering factors such as the type of occupancy, the materials used in construction, and the presence of flammable substances. This assessment was used to determine the appropriate level of fire protection required [2].

Space utilization requirements also play a crucial role. The layout of the sprinkler system was designed to ensure comprehensive coverage while minimizing interference with normal activities in the building. For instance, in industrial facilities with large machinery, the sprinklers need to be positioned in a way that they can effectively reach all potential fire sources without obstructing the operation of the equipment. In civil buildings like offices or residential units, the sprinkler layout should blend in with the interior design and not cause inconvenience to the occupants.

By integrating fire risk assessment and space utilization requirements, a rational design framework for sprinkler layouts were established. This framework guides the determination of the number, type, and location of sprinklers, ensuring that the automatic sprinkler system can function optimally to suppress fires promptly and protect the safety of people and property within the building.

2.2. Hydraulic calculation methodology

Hydraulic calculation in the design of automatic sprinkler systems was crucial for ensuring their effective performance. According to NFPA 13 standards and considering building occupancy characteristics, a proper methodology was required to be adopted. The process typically involves determining the flow rate required for each sprinkler based on factors such as the type of occupancy, hazard classification, and sprinkler spacing. For different building occupancies, like light, ordinary, or high hazard areas, the design criteria vary significantly.

The flow pressure relationship was calculated to ensure that each sprinkler received the appropriate amount of water at the correct pressure. This requires considering the friction losses in the pipes, elevation differences within the building, and the available water supply pressure. Computational methods were used, with algorithms that can simulate the flow distribution in the pipe network. These algorithms help in optimizing the pipe network topology to achieve flow pressure balance. By using such hydraulic calculation methodology, designers can ensure that the automatic sprinkler system functions as intended, providing reliable fire protection for the building and its occupants [3]. It enables the accurate sizing of pipes, selection of appropriate pumps, and determination of the overall system layout to meet the firefighting requirements effectively.

3. Multi-objective optimization strategies

3.1. Water efficiency enhancement approaches

To enhance water efficiency in the automatic sprinkler fire extinguishing systems of building fire protection, two key approaches can be implemented: variable flow sprinkler technology and reclaimed water utilization mechanisms.

Variable flow sprinkler technology allows for the adjustment of water flow based on the intensity of the fire. In the initial stages of a fire, when the scale was relatively small, the sprinklers can operate with a lower water flow rate, which was sufficient to control the fire spread. As the fire intensifies, the flow rate was then increased accordingly. This not only ensures effective firefighting but also significantly reduced unnecessary water consumption during less severe fire situations [4].

The utilization of reclaimed water mechanisms was another important aspect. Reclaimed water, which has been treated to meet certain quality standards, can be sourced from sources such as treated sewage or rainwater collected from the building’s roof. By using reclaimed water in the sprinkler systems, the demand for fresh water can be greatly decreased. However, it was crucial to ensure that the reclaimed water does not cause any damage to the sprinkler components, such as corrosion or blockage. Therefore, appropriate water treatment and monitoring processes need to be in place to guarantee the long-term performance and reliability of the system. These two approaches combined can effectively minimize water consumption while maintaining the necessary firefighting capacity in building fire protection systems.

3.2. Energy-smart system integration

Developing pump frequency conversion control strategies and thermal load responsive activation protocols is crucial for reducing energy expenditure in automatic sprinkler fire extinguishing systems within building fire protection setups. Pump frequency-conversion control can adjust the pump's operating speed according to the actual water demand. In a non-fire situation or when the fire scale is small, the pump can operate at a lower speed, consuming less energy. This not only helps in energy conservation but also extends the service life of the pump and related equipment.

Thermal load responsive activation protocols, on the other hand, ensure that the sprinkler system activates precisely when necessary. By accurately detecting the thermal load in the building environment, the system can start the sprinklers only in areas where there is a real fire threat. This prevents unnecessary activation of the entire system, thus reducing water and energy waste.

For example, advanced sensors were installed throughout the building to monitor temperature changes and heat fluxes. These sensors can communicate with a central control unit that is programmed to analyze the data and make decisions regarding the activation of the sprinkler system. This integration of smart control strategies based on pump frequency conversion and thermal load responsiveness can achieve multi objective optimization, including energy saving, efficient firefighting, and cost effectiveness in building fire protection systems [5].

4. Green building compliance and innovation

4.1. Sustainable material applications

4.1.1. Eco-friendly pipe materials

In the context of green building compliance and innovation, the application of ecofriendly pipe materials in automatic sprinkler fire extinguishing systems was of great significance. When evaluating corrosion resistant composite materials for these systems, it was essential to consider their lifecycle environmental impacts [6].

Firstly, corrosion resistant composite pipe materials can offer enhanced durability, reducing the need for frequent replacements. This not only cuts down on material waste but also decreases the energy consumption associated with production and installation. For instance, some composite pipes made from recycled polymers can maintain their structural integrity and firefighting performance over a long period.

Secondly, the environmental impact throughout the lifecycle of these materials must be carefully analyzed. The extraction of raw materials, the manufacturing process, the transportation to the construction site, and the end-of-life disposal all contribute to the overall environmental footprint. Materials with low energy manufacturing processes and high recyclability are more favorable. For example, certain composite pipes can be easily recycled at the end of their service life, minimizing the amount of waste sent to landfills.

Furthermore, ecofriendly pipe materials should also meet the strict performance requirements of automatic sprinkler systems. They need to withstand high water pressures, resist chemical corrosion from water additives, and maintain their fire-resistant properties. Only by ensuring both environmental friendliness and high performance can these materials truly contribute to the sustainable development of building fire protection systems while adhering to green building compliance standards.

4.1.2. Recyclable component design

Developing modular sprinkler assemblies with disassembly friendly connections is crucial for recyclable component design in the context of green building compliance and innovation. By creating modular designs, each part of the sprinkler assembly can be easily separated. This not only simplifies the repair process but also significantly enhances recyclability. When a component fails, instead of discarding the entire sprinkler unit, only the faulty module needs to be replaced.

The use of disassembly friendly connections, such as quick release couplings or snap fit mechanisms, enables easy separation of different components. These connections should be designed to withstand the operational pressures within the automatic sprinkler system while still allowing for disassembly without causing damage to the parts. This way, at the end of life of the sprinkler system, the components can be efficiently sorted and recycled.

For instance, the metal parts of the modular sprinkler can be melted down and reused in the production of new sprinkler components or other metal products. The plastic components, if made from recyclable polymers, can also be processed and remolded into new plastic parts. This approach aligns with the principles of the circular economy, reducing waste and conserving resources. Overall, such recyclable component design in automatic sprinkler systems is an important step towards sustainable building fire protection and green building compliance [7].

4.2. Smart monitoring integration

4.2.1. IoT-enabled leakage detection

IoT Enabled Leakage Detection is a crucial aspect in the smart monitoring integration for automatic sprinkler fire extinguishing systems within building fire protection. By leveraging the power of the Internet of Things (IoT), highly sensitive sensors can be deployed throughout the pipeline network of the sprinkler system. These sensors are designed to detect even the slightest signs of leakage, which could otherwise go unnoticed and lead to system inefficiencies or complete failures during a fire emergency [8].

The IoT enabled sensors operate by constantly monitoring parameters such as water pressure, flow rate, and vibration patterns within the pipes. A sudden drop in pressure or an abnormal change in flow rate could indicate a potential leakage point. Vibration sensors can also detect the unique patterns associated with water escaping from the pipeline. Once a potential leakage is detected, the sensor immediately sends a real time alert to a central monitoring station. This allows maintenance crews to respond promptly, minimizing water damage to the building and ensuring the integrity of the fire extinguishing system.

Moreover, the data collected by these IoT sensors can be analyzed over time to predict potential leakage locations. Through advanced analytics, trends in pressure changes and flow irregularities can be identified, enabling proactive maintenance. For example, if a particular section of the pipeline consistently shows minor pressure fluctuations, it can be flagged for further inspection before a full-blown leak occurs. This not only improves the reliability of the automatic sprinkler system but also aligns with the principles of green building compliance by reducing water waste and preventing unnecessary damage to the building structure.

4.2.2. BIM-based maintenance systems

Building Information Modeling (BIM) technology offers a revolutionary approach to the maintenance of automatic sprinkler fire extinguishing systems in building fire protection. By creating digital twins of sprinkler systems, it enables more precise and efficient maintenance scheduling.

With BIM, all relevant information about the sprinkler system, such as the type, location, and installation date of each component, can be integrated into a single digital model. This comprehensive database allows maintenance personnel to quickly access and analyze data, facilitating a better understanding of the system's overall condition. For example, when a component approaches its expected service life, the BIM based system can send out alerts, enabling proactive maintenance.

Moreover, BIM based maintenance systems can simulate the performance of the sprinkler system under different scenarios. This helps in predicting potential failures and developing preventive measures. By running virtual tests on the digital twin, maintenance teams can optimize the maintenance plan, ensuring that resources are allocated effectively. For instance, they can determine the most appropriate time to replace a part to minimize system downtime and cost. In addition, the digital twin can be used to train new maintenance staff, providing them with a realistic and safe environment to practice maintenance procedures. Overall, BIM based maintenance systems enhance the maintenance efficiency and reliability of automatic sprinkler fire extinguishing systems, making a significant contribution to building fire protection [9].

5. Practical implementation and validation

5.1. Industrial building case studies

5.1.1. High-risk manufacturing facility retrofit

In the retrofit of high-risk manufacturing facilities, practical implementation and validation play a crucial role in demonstrating water consumption reduction through optimized nozzle configurations and pressure zoning in automatic sprinkler fire extinguishing systems.

Firstly, for the practical implementation, detailed on-site surveys are carried out in high-risk manufacturing facilities such as chemical plants. This includes mapping out the layout of production areas, storage locations of hazardous substances, and existing firefighting infrastructure. Based on this information, engineers design optimized nozzle configurations. For example, in areas with higher fire risks, like where highly flammable chemicals are stored, nozzles with a higher discharge rate and a wider spray angle are installed. These nozzles are carefully spaced to ensure comprehensive fire coverage.

Regarding pressure zoning, the facility was divided into different zones according to the fire risk levels and the height of the building. High risk areas may be in a separate high-pressure zone, while relatively low risk areas were in a lower pressure zone. This zoning was achieved through the installation of pressure regulating valves and appropriate pipe sizing.

After implementation, validation is essential. Firefighting performance tests are conducted in the retrofitted high risk manufacturing facility. These tests simulate different fire scenarios, such as small-scale chemical spills catching fire. Water consumption data is collected during the tests. By comparing the water consumption in the optimized system with the previous unoptimized system, the effectiveness of the optimized nozzle configurations and pressure zoning can be clearly demonstrated. If the water consumption is significantly reduced while still ensuring effective fire suppression, it validates the retrofit strategy, which can serve as a reference for other similar high risk manufacturing facilities [10].

5.1.2. Warehouse protection system upgrade

In the upgrade of the warehouse protection system, the implementation of early suppression fast response (ESFR) technology with energy recovery mechanisms was crucial. First, in terms of practical implementation, the layout of ESFR sprinklers needs to be carefully designed. According to the size, height, and storage type of the warehouse, the appropriate number and spacing of sprinklers were determined. For example, in a large-scale high rack warehouse storing combustible goods, more sprinklers may be required at closer intervals compared to a general-purpose warehouse.

The energy recovery mechanisms are then integrated into the water supply system of the sprinkler system. This can involve installing energy recovery turbines in the return water pipelines. These turbines can capture the energy from the water flow during the operation of the sprinkler system and convert it into electrical energy, which can be reused for other low power operations in the warehouse, such as lighting or ventilation fans.

For validation, a series of fire simulation tests were carried out. These tests simulate different fire scenarios, including the location, scale, and combustion rate of the fire. The performance of the ESFR sprinklers in terms of fire suppression speed, water coverage area, and energy recovery efficiency was measured. For instance, the time it takes for the sprinklers to control the fire and the amount of energy recovered during the firefighting process are recorded. Based on the test results, further optimization can be made to the design of the warehouse protection system. This approach ensures that the upgraded warehouse protection system not only effectively suppresses fires but also achieves energy saving goals, which is in line with the requirements of modern sustainable industrial building design [11].

5.2. Civil building demonstrations

5.2.1. High-rise residential water conservation

In LEED certified high rise residential towers, implementing pressure regulated sprinklers integrated with greywater systems for water conservation in building fire protection systems is a practical approach. Pressure regulated sprinklers are designed to maintain a consistent water flow rate regardless of the supply pressure variations. This feature not only ensures effective fire suppression but also helps in conserving water by preventing over spraying.

When integrating with greywater systems, greywater, which is the relatively clean wastewater from sources like sinks, showers, and washing machines, can be treated and reused in the sprinkler system. This significantly reduces the reliance on fresh water resources.

For practical implementation, a comprehensive design plan is required. The greywater treatment plant needs to be carefully located within the building to ensure smooth operation and easy maintenance. Piping systems for both greywater supply and sprinkler distribution should be well designed to avoid cross contamination and ensure proper water flow.

Validation of this approach is crucial. It can be achieved through a series of tests. Flow rate and pressure tests are carried out to ensure that the pressure regulated sprinklers function as expected. Microbiological and chemical tests are conducted on the treated greywater to verify its compliance with the standards for use in fire protection systems. Additionally, long term monitoring of water consumption and firefighting effectiveness can provide valuable data for further optimization [12]. This combination of practical implementation and validation in high rise residential buildings can lead to more sustainable and efficient automatic sprinkler fire extinguishing systems.

5.2.2. Mixed-use complex system integration

In the practical implementation and validation of mixed-use complex system integration for civil building demonstrations in the context of coordinating sprinkler networks with HVAC and lighting systems for holistic energy management, several key aspects need to be addressed. First, during the implementation phase, detailed design blueprints of the sprinkler, HVAC, and lighting systems should be carefully reviewed and integrated. For example, the layout of sprinkler pipes should be planned in a way that it does not interfere with the ductwork of the HVAC system, while also considering the positioning of lighting fixtures to ensure unobstructed water spray in case of a fire [13].

Sensors play a crucial role in this integration. Smoke and heat sensors in the sprinkler system can be linked to the HVAC system to adjust air circulation in case of a fire, preventing the spread of smoke. At the same time, the lighting system can be programmed to switch to emergency lighting mode when the sprinkler system is activated.

Validation is then carried out through a series of tests. Simulated fire scenarios are created in a test area of the mixed-use complex. The performance of the integrated system is monitored, including the activation time of the sprinkler system, the response of the HVAC system in terms of air control, and the speed at which the lighting system switches to emergency mode. Any discrepancies found during the tests are analyzed, and corresponding adjustments are made to the system design. This iterative process of implementation and validation helps to ensure the efficient and reliable operation of the integrated system in real world civil building applications.

5.3. Performance benchmark analysis

5.3.1. Water-energy nexus metrics

In the practical implementation and validation of the design and optimization strategy for automatic sprinkler fire extinguishing in building fire protection systems, the water energy nexus metrics play a crucial role. These metrics are designed to evaluate the tradeoffs and synergies between water consumption and energy use in the system.

For traditional automatic sprinkler systems, a certain amount of water was required to be discharged at a specific pressure to effectively suppress fires. The energy is mainly consumed in pumping water to reach the required pressure for sprinkler operation. When optimizing the system, new materials, more efficient pump designs, or intelligent control strategies might be introduced. For example, using variable speed pumps can adjust the energy input according to the actual water demand during a fire event, potentially reducing overall energy consumption while maintaining effective water discharge [14].

To measure the water energy nexus, metrics such as water energy ratio (the amount of water used per unit of energy consumed) can be calculated. A higher water energy ratio indicates a more efficient use of resources, meaning that more water can be delivered to suppress the fire with less energy input. Additionally, metrics like total water consumption during a fire scenario and the corresponding energy input for different system configurations (traditional and optimized) can be compared. These benchmark analyses based on water energy nexus metrics help in validating whether the optimization strategies not only improve firefighting effectiveness but also enhance the resource use efficiency in the automatic sprinkler fire extinguishing systems.

5.3.2. Lifecycle cost-benefit projections

For the performance benchmark analysis of the automatic sprinkler fire extinguishing system in building fire protection, a series of metrics need to be established. These may include response time, water distribution uniformity, and fire suppression effectiveness. Response time is crucial as it determines how quickly the system can start working once a fire is detected. A shorter response time can significantly reduce the spread of the fire. Water distribution uniformity ensures that the entire fire prone area is adequately covered with water, maximizing the fire extinguishing effect. Fire suppression effectiveness can be measured by the ability to control and extinguish fires of different scales and types.

When making lifecycle cost benefit projections for different design scenarios of the automatic sprinkler system, consider all costs and benefits over a 20 years period. Costs include initial installation costs, which cover equipment purchase, piping installation, and system commissioning. Maintenance costs are also significant, involving regular inspections, component replacements, and system upgrades. Energy costs for operating the system, such as pump power consumption, should not be overlooked. On the benefit side, the most obvious is the potential reduction in property damage and loss of life due to effective fire suppression. Additionally, in some regions, buildings with compliant automatic sprinkler systems may receive insurance premium discounts, which is also a long-term benefit. By comprehensively evaluating these costs and benefits, a more accurate projection of the lifecycle cost benefit of different design scenarios can be obtained, providing a solid basis for decision making in system design and optimization.

6. Conclusion

In conclusion, the design and optimization strategy of automatic sprinkler fire extinguishing in building fire protection systems is a complex yet crucial topic. The synthesized findings highlight the significance of achieving a balanced optimization between ensuring fire safety and sustainable resource utilization. This balance was not only essential for immediate fire protection but also for the long term environmental and economic viability of buildings.

The proposed adaptive design frameworks tailored to various building typologies offer a practical approach. Different building types, such as residential, commercial, and industrial, have unique fire risks and usage patterns. By adapting the design of automatic sprinkler systems accordingly, we can enhance their effectiveness.

Looking ahead, future research directions in AI driven predictive system tuning hold great promise. AI can analyze a vast amount of data, including historical fire incidents, building occupancy, and environmental factors, to predict fire risks more accurately. This enables pre-emptive activation of sprinkler systems and better resource allocation. Additionally, the application of nanomaterials in sprinkler systems could potentially revolutionize their performance. Nanomaterials may offer enhanced heat dissipation properties, corrosion resistance, and more efficient water distribution, further improving the overall fire extinguishing capabilities. Overall, continuous research and innovation in these areas will contribute to the development of more advanced and effective automatic sprinkler fire extinguishing systems in building fire protection.

Disclosure statement

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Research on Key Technologies and Quality Control of Installation and Construction of Building HVAC Equipment

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Abstract: Building HVAC equipment installation is vital for indoor comfort, energy efficiency, and environmental quality. Key technologies like vibration control, pipe network alignment, and thermal stress compensation, along with a multi-faceted quality standards framework, are crucial. Effective process management, practical application analysis, and the integration of robotics, IoT, and AI enhance quality and efficiency. Sustainable development strategies and lifecycle-oriented quality management are also essential for future progress.

Keywords: HVAC equipment installation; Key technologies; Quality control

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1. Introduction

In the realm of building construction, the installation and construction of HVAC equipment hold great importance. With the construction industry's continuous evolution and the escalating demand for high quality indoor environments, the study of key technologies and quality control in this area has become a crucial academic pursuit. For instance, vibration control, as one of the critical technologies in HVAC equipment installation, has been systematically reviewed in recent research, highlighting its significance in ensuring operational stability and reducing noise [1]. In line with the global trend towards sustainable development, policies such as the "Sustainable Energy for All" initiative launched in 2012 encourage the integration of energy efficient and environmentally friendly practices in building systems, including HVAC. This paper delves into the key technologies, quality control, and practical applications in HVAC equipment installation, exploring how to enhance installation levels while adhering to sustainable development principles, aiming to provide theoretical and practical guidance for the industry.

2. Core technologies for HVAC equipment installation

2.1. Installation process design

For the installation process design of building HVAC equipment, under complex building structures, it is essential to consider the systematic installation flow design principles. First, the layout of the equipment needs to be carefully planned. This requires taking into account factors such as the building's architectural features, space utilization, and the intended functionality of the HVAC system. For example, the location of air handling units should be determined based on the distribution of air supply and return ducts to ensure efficient air circulation [2].

Workflow optimization strategies also play a crucial role. One aspect is to streamline the sequence of installation tasks. For large scale HVAC equipment, tasks like equipment transportation, assembly, and pipeline connection need to be arranged in a logical order to minimize delays and rework. For instance, pre assembly of components off-site can be carried out to reduce on-site installation time. Additionally, modern project management tools and techniques can be applied to monitor and control the installation process. This includes using scheduling software to set milestones and allocate resources effectively, ensuring that the entire installation project progresses smoothly and is completed within the specified time and budget constraints. By adhering to these systematic installation flow design principles and implementing workflow optimization strategies, the installation of building HVAC equipment can be carried out more efficiently and with higher quality.

2.2. Key technical challenges

One of the key technical challenges in HVAC equipment installation lies in vibration control during mechanical installation. The operation of HVAC mechanical components can generate significant vibrations, which not only cause noise pollution, affecting the comfort of the building occupants, but also potentially lead to damage to the equipment itself over time due to fatigue stress [3]. Precise installation techniques and the use of appropriate vibration isolation materials are crucial to mitigate these vibrations.

Another challenge is the pipe network alignment precision. In an HVAC system, a complex network of pipes is used to transport air, water, or refrigerants. Any misalignment in the pipes can disrupt the fluid flow, leading to inefficiencies in the system. This requires highly accurate measurement tools and skilled installers to ensure that the pipes are aligned correctly, both horizontally and vertically, to maintain the smooth operation of the system.

Thermal stress compensation in HVAC system connections is also a significant challenge. As the HVAC system operates, temperature changes can cause expansion and contraction of the pipes and equipment. If not properly compensated for, these thermal stresses can cause leaks in the connections, or even structural damage to the pipes. Designing effective thermal expansion joints and using materials with appropriate thermal expansion coefficients are necessary to address this challenge.

3. Quality control system construction

3.1. Quality standards framework

The quality standards framework for the installation and construction of building HVAC equipment is multi-faceted. It integrates ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) standards, which are widely recognized in the field of HVAC. ASHRAE standards cover various aspects such as energy efficiency, indoor air quality, and system performance [4]. These standards ensure that the HVAC systems are designed and installed to meet a certain level of technical performance, for example, setting limits on the energy consumption of different types of HVAC equipment.

LEED (Leadership in Energy and Environmental Design) certification requirements are also incorporated. LEED focuses on the overall environmental impact of the building, including the role of the HVAC system. It promotes sustainable design and operation of HVAC systems, such as encouraging the use of renewable energy sources in HVAC operations, improving the energy recovery efficiency of the system, and reducing greenhouse gas emissions.

Regional construction codes play a crucial part as well. These codes are tailored to the local climate, building types, and safety requirements. For instance, in areas with extreme climates, the codes may require higher insulation levels for HVAC ducts to minimize heat loss or gain. They also ensure that the installation and construction of HVAC equipment meet local safety regulations, like proper grounding of electrical components in the HVAC system. By integrating these three elements ASHRAE standards, LEED certification requirements, and regional construction codes a comprehensive quality standards framework is established for the installation and construction of building HVAC equipment.

3.2. Process management measures

To ensure the quality of building HVAC equipment installation and construction, effective process management measures are crucial. Firstly, a detailed construction plan should be formulated. This plan should cover every step of the installation process, from equipment delivery and inspection to actual installation and commissioning. By doing so, potential issues can be anticipated in advance, and corresponding countermeasures can be prepared.

Secondly, strict control over construction operations is essential. Workers need to follow standardized operating procedures. For example, when installing pipes, attention should be paid to the slope, connection tightness, and insulation measures to prevent problems such as water leakage and heat loss. Supervisors should regularly inspect the construction site to ensure that all operations comply with the requirements.

In addition, real time monitoring solutions for critical installation nodes should be implemented, as developed in the BIM based collaborative management mechanisms [5]. This enables timely detection of any deviations from the standard during the installation process. Through real time data collection and analysis, immediate adjustments can be made, thus reducing the risk of quality problems. Regular communication among different teams involved in the project, including designers, installers, and supervisors, is also necessary. This can help resolve potential conflicts promptly and ensure the smooth progress of the installation work. Overall, these process management measures contribute to the high-quality installation and construction of building HVAC equipment.

4. Practical application analysis

4.1. Case study methodology

4.1.1. Project background selection

In the research on the key technologies and quality control of the installation and construction of building HVAC equipment, representative commercial complex projects are chosen as the research objects. Commercial complexes typically feature large scale areas, high density occupancies, and diverse functional zones, such as shopping areas, dining areas, and entertainment areas. These characteristics demand a high performance and well configured HVAC system to ensure comfortable indoor environmental conditions.

The diversified HVAC system configurations in these commercial complex projects play a crucial role. For example, variable refrigerant flow (VRF) systems may be employed in some areas for their flexibility in temperature control and energy saving features. Central air conditioning systems, on the other hand, could be utilized in large scale open plan areas to provide uniform cooling or heating. The presence of such diverse configurations allows for a comprehensive study of different key installation technologies, such as refrigerant pipe installation in VRF systems and ductwork installation in central air conditioning systems.

Moreover, by focusing on commercial complex projects, the study can better address the real-world challenges in quality control during HVAC equipment installation and construction. These challenges include coordinating with other building systems, meeting strict indoor air quality requirements, and ensuring long - term reliable operation. Such research based on commercial complex projects can offer practical and valuable insights, which are of great significance for promoting the overall quality of building HVAC equipment installation and construction [6].

4.1.2. Technical implementation evaluation

In the Technical Implementation Evaluation within the Practical Application Analysis through Case Study Methodology, a comparative analysis of equipment installation efficiency and system performance metrics before and after the technology application is of great significance. This evaluation aims to precisely measure the real-world impact of the key technologies in the installation and construction of building HVAC equipment.

Regarding equipment installation efficiency, factors such as the time taken for component assembly, the number of workers involved, and the frequency of installation related issues are carefully examined. By comparing the pre technology application situation with the post implementation scenario, it becomes possible to determine whether the new technologies have led to a reduction in installation time, an optimization of labor resources, or a decrease in installation related setbacks. For instance, advanced prefabrication techniques might have enabled quicker on-site assembly, thus enhancing the overall installation efficiency [7].

System performance metrics, on the other hand, cover aspects like energy consumption, indoor air quality, and temperature and humidity control accuracy. A lower energy consumption rate after the technology implementation indicates improved energy saving performance. Enhanced indoor air quality could imply that the new technologies have optimized air filtration and ventilation mechanisms. Precise temperature and humidity control showcases the effectiveness of control algorithms and sensor technologies. Through this comprehensive evaluation of equipment installation efficiency and system performance metrics, a clear understanding of the practical effectiveness of the key technologies in the installation and construction of building HVAC equipment can be obtained, providing valuable insights for future improvements and applications.

4.2. Quality performance verification

4.2.1. System stability testing

Under full load conditions, the system stability testing of building HVAC equipment installation and construction focuses on operational vibration analysis and thermal cycle testing. Operational vibration analysis is crucial as excessive vibration not only affects the comfort of the building occupants but also poses a threat to the long-term operation of the equipment. By measuring and analyzing vibration parameters such as amplitude, frequency, and direction during the full load operation of the HVAC equipment, potential problems like unbalanced rotors, loose components, or improper installation can be detected [8]. For instance, if the vibration amplitude exceeds the standard value, it might indicate that the fan blades are not properly balanced, which could lead to accelerated wear and tear of bearings and ultimately equipment failure.

Thermal cycle testing, on the other hand, simulates the actual working environment of the HVAC system where temperature changes occur cyclically. This helps to assess the adaptability of the equipment to different temperature conditions. During the test, the system is subjected to a series of temperature rises and drops. The equipment's performance, including its cooling or heating capacity, energy consumption, and the stability of key components, is closely monitored. If the equipment fails to maintain stable performance during thermal cycling, it may suggest issues with the thermal management system, such as ineffective insulation or improper refrigerant flow control. Overall, these two aspects of system stability testing are essential for ensuring the reliable and long-term operation of building HVAC equipment.

4.2.2. Energy efficiency validation

In the Energy Efficiency Validation within the Practical Application Analysis of Quality Performance Verification, EnergyPlus software is employed to conduct a comprehensive energy consumption simulation. This simulation meticulously models the energy usage patterns of the building HVAC equipment under various scenarios, taking into account factors such as building orientation, insulation properties, occupancy schedules, and equipment operation characteristics. By accurately simulating the energy consumption, it provides a theoretical baseline for evaluating the energy efficiency of the HVAC system.

Subsequently, field measurement data are collected. These data are obtained from actual operating conditions of the installed HVAC equipment in the building. The measured parameters may include power consumption of different components, indoor and outdoor temperature differentials, air flow rates, and energy consumption of the entire system over a specific period.

The energy consumption simulation results and the field measurement data are then compared. This comparison serves as a crucial means to validate the energy efficiency of the building HVAC equipment installation and construction. Any significant discrepancies between the simulation and measurement may indicate issues in the design, installation, or operation of the equipment. For instance, if the measured energy consumption is much higher than the simulated value, it could imply problems such as improper equipment sizing, inefficient installation leading to energy losses, or suboptimal control strategies. Through this in - depth comparison and analysis, the energy efficiency of the building HVAC equipment can be effectively verified, providing valuable insights for further improvement and quality control in the installation and construction process [9].

5. Technical optimization suggestions

5.1. Intelligent installation innovation

5.1.1. Robotics integration

The integration of robotics in the installation and construction of building HVAC equipment represents a significant step forward in intelligent installation innovation. By leveraging SLAM navigation technology, automated alignment solutions for heavy equipment installation can be achieved.

Robots equipped with advanced sensors can precisely map the installation environment, creating a real-time three-dimensional model. This model allows the robots to plan optimal paths for equipment transportation and installation, avoiding obstacles and ensuring accurate alignment. For example, in a large-scale commercial building’s HVAC system installation, robots can navigate through complex spaces such as basements and mechanical rooms.

These robots are designed to handle the heavy lifting tasks associated with HVAC equipment. They can lift, position, and align components with a high degree of precision, reducing human error. In terms of quality control, the robotic systems can continuously monitor the installation process, collecting data on parameters such as alignment accuracy, connection tightness, etc. Any deviations from the set standards can be immediately detected and corrected.

Furthermore, the use of robotics in this field also improves work efficiency. Multiple robots can work simultaneously, coordinated by a central control system, to complete different stages of the installation process in parallel. In conclusion, the integration of robotics, especially when combined with SLAM navigation technology, offers a promising solution for the key technologies and quality control in the installation and construction of building HVAC equipment [10].

5.1.2. IoT-enabled monitoring

In the context of the installation and construction of building HVAC equipment, an IoT-enabled monitoring system with a proposed wireless sensor network architecture plays a crucial role. This architecture is designed to achieve real - time stress/strain monitoring during the installation phases [11]. By leveraging IoT technology, a network of wireless sensors can be strategically placed on the HVAC equipment and relevant installation structures. These sensors are capable of accurately detecting and transmitting data regarding stress and strain in real time. This real time data collection enables installation teams to closely monitor the physical conditions of the equipment during installation. For example, sudden changes in stress or strain values can indicate potential problems such as improper installation, unbalanced loads, or structural defects. The data transmitted by the sensors can be received and analyzed through a central monitoring platform. The platform uses advanced algorithms to process the data, providing intuitive visualizations and alerts. This allows installers to make timely adjustments and corrections, ensuring the installation process proceeds smoothly and the long-term stability and safety of the HVAC equipment. The IoT enabled monitoring not only improves the quality control during the installation but also contributes to reducing the risk of future malfunctions and maintenance costs associated with the building's HVAC system.

5.2. Quality assurance enhancement

5.2.1. Digital twin applications

Developing physics based digital twin models is a crucial step in achieving predictive quality control in HVAC component assembly. These digital twin models are constructed based on the physical principles governing the operation of HVAC components. For instance, they incorporate factors such as heat transfer, fluid dynamics, and thermodynamics relevant to the specific component being modeled [12].

By creating these models, it becomes possible to simulate the assembly process in a virtual environment. This simulation can predict potential quality issues before they occur in the actual physical assembly. For example, the model can detect if there will be misalignments in pipes during the connection process, or if certain parts might experience excessive stress due to improper installation sequences.

Furthermore, the digital twin models can be updated in real time with data from sensors placed on the actual components during the assembly process. This real time data enables the model to adapt and provide more accurate predictions, continuously enhancing the quality control process. The digital twin also serves as a valuable tool for training personnel. Trainees can practice the assembly process using the digital twin, familiarizing themselves with the correct procedures and potential problem-solving methods, thus reducing the likelihood of quality - related mistakes during actual on-site assembly. Overall, the physics based digital twin models play a vital role in ensuring high quality HVAC component assembly.

5.2.2. AI-driven defect detection

AI driven Defect Detection can be realized by implementing deep learning algorithms. Point cloud data analysis serves as a crucial tool in this process. Point cloud data, which can comprehensively represent the geometric information of the HVAC equipment and its installation environment, is collected from the installation site. Deep learning-based algorithms are then applied to analyze this data [13]. These algorithms are trained to recognize patterns that indicate installation deviations. For example, convolutional neural networks (CNNs) can be used to process the point cloud data. CNNs are good at extracting local features from data. They can identify whether the position of the equipment is off set, if the angles of components are incorrect, or if there are any missing parts in the installation. Through continuous training with a large number of labeled point cloud data samples, the algorithm can improve its accuracy in identifying installation defects. Once the algorithm is well trained, it can automatically detect potential defects during the installation and construction process of building HVAC equipment in real time. This not only improves the efficiency of defect detection but also enhances the accuracy, reducing the reliance on manual inspection and minimizing human error related omissions in defect identification.

5.3. Sustainable development strategies

5.3.1. Low-carbon installation techniques

Researches prefabricated modular installation methods to minimize construction waste generation. This approach is of great significance for achieving low carbon installation in the building HVAC equipment installation and construction. By adopting prefabricated modular installation, a large part of the manufacturing process can be carried out in a factory environment. This not only improves production efficiency but also reduces on-site cutting, welding and other operations, thereby significantly reducing the generation of construction waste such as scraps and dust [14].

In the factory, with advanced production equipment and standardized production processes, the accuracy and quality of modular components can be better guaranteed. These prefabricated modules can be directly transported to the construction site for assembly, which simplifies the on-site installation process. Workers only need to connect the modules according to the design requirements, reducing the complexity and time consumption of on-site construction.

Moreover, the prefabricated modular installation method is conducive to the reuse and recycling of materials. When the HVAC equipment needs to be updated or maintained in the future, the modular components can be easily disassembled. Some components in good condition can be reused, and the waste components can also be recycled more conveniently according to their material properties, further promoting the sustainable development of the construction industry.

5.3.2. Lifecycle-oriented quality management

When it comes to the installation and construction of building HVAC equipment, establishing maintenance focused quality tracking mechanisms considering equipment service lifecycle characteristics is crucial.

Throughout the equipment's lifecycle, from the initial installation phase to its long-term operation and eventual decommissioning, quality management should be an ever-present concern. During installation, strict quality control measures need to be implemented. This includes ensuring that components are correctly installed, connections are secure, and the overall system is configured to meet design specifications. Meticulous inspection at this stage can prevent potential problems from emerging during operation.

As the equipment enters the operation phase, continuous quality tracking is essential. Regular monitoring of key performance indicators such as energy consumption, temperature regulation accuracy, and air quality can help detect early signs of degradation or malfunction. Based on the data collected, predictive maintenance strategies can be formulated. For example, if the energy consumption of an air conditioning unit starts to increase steadily without a corresponding change in usage patterns, it could indicate a problem with the compressor or refrigerant system, prompting timely maintenance.

Finally, at the end-of-life stage, proper disposal and recycling of HVAC equipment should be part of the quality management process. This not only ensures environmental sustainability but also reflects the overall quality commitment to the entire lifecycle of the equipment. By comprehensively managing quality throughout the equipment's lifecycle, the long-term performance, reliability, and sustainability of building HVAC systems can be significantly enhanced.

6. Conclusion

In conclusion, the installation and construction of building HVAC equipment are of great significance in the construction industry. The key technologies, such as precise equipment positioning, efficient pipeline connection, and intelligent control system integration, have witnessed remarkable technological breakthroughs. These advancements not only improve the installation efficiency but also enhance the overall performance of HVAC systems.

Regarding quality control, proactive methodologies, including strict pre-installation inspections, in process quality monitoring, and comprehensive post-installation testing, have been proven effective in ensuring the reliability and durability of HVAC installations.

Looking ahead, the future of HVAC installation technologies lies in the integration of sustainability and digital transformation. Incorporating renewable energy sources into HVAC systems, such as solar powered air conditioning units, can significantly reduce the environmental impact. Digital transformation, on the other hand, enables real time monitoring, predictive maintenance, and intelligent optimization of HVAC operations. This will lead to more energy efficient, cost effective, and user-friendly building environments. Overall, continuous innovation in key technologies and strict quality control will be the cornerstones for the sustainable development of building HVAC equipment installation and construction.

Disclosure statement

The author declares no conflict of interest.

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Practical Research on the Effective Management of Change Visas and Dynamic Cost Control in the Construction Stage of Construction Projects

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Abstract: Construction project construction stage requires effective change visa management and dynamic cost control. This paper defines both, presents related theories, and details challenges in traditional methods. It then proposes an integrated model with system architecture, functional modules, and practical strategies like BIM integrated workflows. A case study validates the effectiveness, and future research on AI enhanced change prediction and blockchain based audit trails is suggested.

Keywords: Change visas; Dynamic cost control; Construction projects

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1. Introduction

In the construction industry, the effective management of change visas and dynamic cost control during the construction stage of projects is of great significance. The "Construction Project Cost Management Regulations" emphasizes the importance of scientific cost management and strict control of project changes. Change visas, which are affected by various factors, can impact project cost, schedule, and quality. Dynamic cost control is essential to ensure projects stay within budget. Traditional methods have limitations, while integrated models, BIM-integrated workflows, such as the BIM-based information management system applied in construction and demolition waste management for greenhouse gas quantification and mitigation and predictive analytics offer solutions [1]. Standardized protocols, cross-departmental collaboration, and modern systems are also crucial. Research on these aspects, as guided by the policy, can help construction project managers improve performance and ensure project success.

2. Theoretical framework and core concepts

2.1. Definition of change visas and dynamic cost control

Change visas, also known as variation orders, in the construction stage of construction projects refer to formal instructions issued by the employer or the engineer to make changes to the original contract scope, quantity, quality, or construction sequence of the project [2]. These changes can be initiated due to various reasons such as design modifications, unforeseen site conditions, or client requested adjustments. Change visas have a direct impact on the project cost, time, and quality. They are crucial documents that need to be carefully managed as they can significantly alter the initial project plan and budget.

Dynamic cost control, on the other hand, is a continuous process of monitoring, analyzing, and adjusting the project cost throughout the construction stage. It involves comparing the actual cost incurred with the planned cost, identifying any variances, and taking appropriate corrective actions. Dynamic cost control is not a static process but rather an iterative one that adapts to the dynamic nature of construction projects. It considers factors like changes in market prices of materials, labor productivity fluctuations, and the impact of change visas. By implementing effective dynamic cost control, project managers can ensure that the project stays within the budget, minimize cost overruns, and achieve the desired economic benefits. Overall, understanding the definitions of change visas and dynamic cost control is fundamental for effective management in the construction stage of construction projects.

2.2. Theoretical basis for cost management

Cost management in construction projects is founded on several key theoretical concepts. Lifecycle cost theory plays a vital role. This theory emphasizes considering all costs associated with a construction project throughout its entire lifecycle, from the initial planning and design phase, through construction, to operation, maintenance, and even demolition [3]. By taking a holistic view of costs, it enables project managers to make more informed decisions. For instance, a more expensive but durable building material might seem costly upfront, but over the long term, it could result in lower maintenance and replacement costs, thus reducing the overall lifecycle cost.

Change management theory is also crucial. In construction projects, changes are inevitable due to various factors like design modifications, unforeseen site conditions, or client requests. This theory provides a structured approach to handle these changes effectively. It involves processes such as change identification, impact assessment, approval, and implementation. Proper change management can prevent cost overruns caused by ad hoc changes, ensuring that any adjustments to the project scope are accompanied by a corresponding evaluation of cost implications.

Real time cost control principles are the third cornerstone. In the fast paced environment of construction, real time monitoring and control of costs are essential. This requires the use of modern technologies and tools to collect, analyze, and report cost data promptly. By having up to date cost information, project managers can quickly identify variances from the budget, take corrective actions, and keep the project's cost performance on track.

3. Current challenges in change visa management and cost control

3.1. Issues in change visa execution

During the execution of change visas in the construction stage of construction projects, several significant challenges emerge. Inefficiencies in approval workflows stand out as a major hurdle. Lengthy and convoluted approval processes can cause substantial delays. For instance, multiple levels of review and sign off, sometimes involving various departments with different priorities and schedules, may lead to bottlenecks. This not only slows down the implementation of change visas but also impacts the overall project timeline, potentially increasing costs due to extended labor and equipment rental periods [4].

Documentation inconsistencies are another crucial issue. Inaccurate, incomplete, or conflicting documentation can create misunderstandings among stakeholders. For example, discrepancies between the description of the change in the visa and the actual work carried out, or between different versions of the same document, can lead to disputes over scope, cost, and quality. These disputes often require additional time and resources to resolve, disrupting the project's progress.

Stakeholder coordination challenges also pose difficulties. Construction projects involve a diverse range of stakeholders, including contractors, subcontractors, designers, and clients. Each stakeholder may have different interests and expectations regarding change visas. For example, contractors may be more concerned with cost effectiveness and timely execution, while clients may focus on achieving the desired functionality. Coordinating these different perspectives and ensuring effective communication is essential. However, misaligned goals, lack of clear communication channels, or poor information sharing can result in inefficiencies and conflicts during the change visa execution process.

3.2. Limitations of traditional cost control methods

Traditional cost control methods in construction projects often face several limitations. One of the major drawbacks is the static budget constraints. These methods typically rely on a fixed budget set at the beginning of the project, assuming that project conditions will remain relatively stable. However, in reality, construction projects are highly dynamic, with numerous factors such as design changes, unforeseen site conditions, and market fluctuations that can impact costs. This static budget fails to adapt to these changes, leading to cost overruns [5].

Another limitation is the delayed cost feedback. Traditional methods usually depend on periodic reports, which means that cost information is not available in real time. By the time the cost deviations are identified, significant cost overruns may have already occurred, leaving little room for effective corrective actions.

Furthermore, traditional cost control methods often lack an adequate response mechanism to dynamic project changes. They are not well equipped to handle the complex and rapid changes that occur during the construction stage, such as change visas. When a change occurs, the existing cost control framework may not be able to accurately assess the impact on costs, allocate resources appropriately, or adjust the cost control strategies promptly. As a result, the project may experience disruptions in cost management, ultimately affecting the overall project performance.

4. Integrated model for dynamic cost control with change visa management

4.1. Framework design of the model

4.1.1. System architecture

The system architecture of the integrated model for dynamic cost control with change visa management aims to seamlessly integrate change visa workflows, real time cost monitoring, and predictive analytics in a closed loop framework.

The change visa workflow component serves as the starting point. It details the entire process from the initiation of a change request due to various project related factors such as design adjustments or unforeseen site conditions. This process involves multiple stakeholders, including contractors, designers, and project managers. Each step of the workflow, from submission, review, approval to implementation, is clearly defined to ensure transparency and accountability [6].

Real time cost monitoring is closely intertwined with the change visa workflow. As the change visa progresses, cost related data is continuously collected. This includes material costs, labor costs, and any additional expenses associated with the change. Advanced cost monitoring tools are employed to track these costs accurately, enabling project teams to have an up to date understanding of the financial implications of each change visa.

Predictive analytics, on the other hand, uses historical data from past change visas and current project data. By applying statistical models and machine learning algorithms, it forecasts potential cost overruns, schedule delays, and other risks associated with the change visas. This proactive approach allows project managers to take preventive measures in a timely manner.

These three components form a closed loop system. The results of predictive analytics can influence the change visa workflow, for example, by suggesting alternative change solutions to avoid excessive costs. Real time cost monitoring feeds back into both the change visa workflow and predictive analytics, providing fresh data for better decision making.

4.1.2. Functional modules

The functional modules of the model include detailed modules for change impact assessment, cost database updating, and risk alert mechanisms. The change impact assessment module is designed to accurately evaluate the influence of change visas on project costs. It analyzes various factors such as changes in work scope, schedule adjustments, and material substitutions caused by change visas, and quantifies their impacts on cost through specific algorithms and data analysis methods [7]. This enables project managers to understand the cost implications of each change visa clearly.

The cost database updating module is crucial for maintaining the accuracy of cost information. As change visas occur, relevant cost data, including new material prices, labor costs for additional work, and equipment rental fees, need to be promptly updated in the cost database. This ensures that the cost data used for cost control and decision making is up to date and reflects the real time situation of the project.

The risk alert mechanism module monitors the cost related risks associated with change visas. By setting up risk thresholds and using risk assessment models, it can timely detect potential cost - overruns or abnormal cost fluctuations caused by change visas. Once a risk is identified, it sends alerts to relevant personnel, enabling them to take preventive measures in a timely manner, such as adjusting the project plan, negotiating with contractors, or re-evaluating the feasibility of change visas. These three functional modules work together to support effective dynamic cost control in construction projects with change visa management.

4.2. Data-driven decision support

4.2.1. BIM-based cost tracking

Developing BIM integrated workflows is crucial for effective cost tracking in the context of change visa management and dynamic cost control. These workflows enable the visualization of change impacts. By integrating Building Information Modeling (BIM) technology, project teams can vividly see how a change visa affects the overall project structure, layout, and components. For example, a design change in a building's façade can be visualized in the BIM model, showing its impact on materials, labor, and time.

Moreover, BIM integrated workflows automate quantity takeoffs. This automation significantly reduces human errors associated with manual quantity calculations. It quickly and accurately determines the quantities of materials such as concrete, steel, and bricks required for a modified part of the project due to a change visa. The accurate quantity data, in turn, is essential for precise cost estimation.

These automated quantity takeoffs and visualizations form the basis of BIM based cost tracking. Cost managers can rely on the data provided by BIM integrated workflows to monitor costs in real time. As changes occur, the BIM model is updated, and the associated cost implications are immediately reflected, allowing for timely decision making. With this approach, cost control becomes more proactive rather than reactive, enabling project teams to stay within budget constraints throughout the construction stage of construction projects [8].

4.2.2. Predictive analytics for cost deviation

Predictive analytics for cost deviation is a crucial component in the integrated model for dynamic cost control with change visa management. Machine learning algorithms are implemented to forecast cost variations resulting from change visas. These algorithms can analyze historical data related to change visas, such as the type of change, the project phase when the change occurred, the involved parties, and the resulting cost impacts. By processing this large volume of data, machine learning models can identify patterns and relationships that are difficult for humans to detect [9]. For example, they may find that certain types of change visas in specific project stages are more likely to lead to significant cost increases. Once these patterns are recognized, the model can predict future cost deviations when new change visas are issued. This enables project managers to anticipate potential cost overruns in advance. They can then take proactive measures, such as re - evaluating the project budget, adjusting resource allocation, or negotiating more favorable terms with contractors. Predictive analytics not only helps in cost control but also improves overall project management efficiency by providing data driven insights for decision - making in the face of change visas.

5. Implementation strategies and case validation

5.1. Process optimization measures

5.1.1. Standardized change authorization protocol

For the standardized change authorization protocol, design streamlined approval hierarchies and digital signature mechanisms for change visas. Simplifying the approval hierarchies is crucial as in traditional construction project change management, complex and multi-level approval processes often lead to inefficiencies, delays, and increased costs. By streamlining these hierarchies, the time from the initiation of a change request to its approval can be significantly reduced. For example, identifying key decision makers at each relevant stage and directly routing the change visa through them can eliminate redundant approval steps.

Digital signature mechanisms play an important role in enhancing the efficiency and security of the change authorization process. Digital signatures ensure the authenticity and integrity of the change visa documents. They enable remote approval, breaking the geographical constraints that may slow down the traditional paper based signature process. This means that stakeholders can review and sign change visas promptly regardless of their location. Moreover, digital signatures are legally recognized in many regions, providing a reliable way to approve change visas. These two aspects, streamlined approval hierarchies and digital signature mechanisms, work in tandem to standardize the change authorization protocol, thus contributing to the effective management of change visas and dynamic cost control in construction projects [10].

5.1.2. Cross-departmental collaboration mechanisms

To enhance cross departmental collaboration mechanisms for effective management of change visas and dynamic cost control in construction projects' construction stage, integrated communication platforms linking design, procurement, and cost teams are essential. These platforms break down the silos between departments. Design teams can promptly share any modifications in the design, which might trigger change visas. For instance, if there is a design alteration to improve the functionality of a building's layout, this information can be instantly conveyed to the procurement team. The procurement team, in turn, can then assess the impact on material costs and availability. They can inform the cost team about potential price fluctuations due to changes in material requirements. The cost team can use this information to accurately update the cost estimates and adjust the dynamic cost control strategies.

In a real world case, a large scale commercial construction project implemented such an integrated communication platform [11]. Initially, without the platform, design changes were often communicated tardily, leading to delays in procurement and unexpected cost overruns. After establishing the platform, all departments were on the same page. When the design team proposed a change to use more energy efficient materials, the procurement team quickly sourced suppliers and provided cost quotes to the cost team. The cost team was able to incorporate these changes into the cost plan in a timely manner, effectively controlling the project cost and minimizing the number of unforeseen change visas.

5.2. Technological enablers

5.2.1. Cloud-based cost management systems

Cloud Based Cost Management Systems play a crucial role in the effective management of change visas and dynamic cost control in the construction stage of construction projects. By deploying centralized databases, these systems enable real time cost data sharing. This means that all relevant parties, including project managers, contractors, and cost estimators, can access the most up to date cost information. For example, when a change visa occurs, the cost impact can be immediately recorded and shared across the team, ensuring that everyone is on the same page regarding the financial implications [12].

Version control is another key feature. It helps to track the evolution of cost data over time. In a construction project, cost estimates may change multiple times due to various factors such as design modifications or market price fluctuations. With version control in cloud - based systems, each change can be documented, allowing for easy review and analysis. This not only provides transparency but also helps in auditing processes. For instance, if there is a dispute regarding a cost item, the historical versions of the cost data can be retrieved to understand how the figure was derived. Overall, cloud based cost management systems enhance the efficiency and accuracy of cost control, facilitating better decision - making during the construction stage.

5.2.2. Mobile reporting tools

Developing field data collection apps for instant change documentation and cost impact calculation is a crucial aspect of mobile reporting tools in the effective management of change visas and dynamic cost control during the construction stage of construction projects. These apps empower construction site personnel to document changes promptly. For example, workers can use their mobile devices to take photos, record descriptions, and note relevant details of any change on-site. This immediate documentation ensures the accuracy and timeliness of data, which is essential for processing change visas accurately.

Simultaneously, these apps can be integrated with cost calculation algorithms. Once the change details are input, the app can quickly calculate the potential cost impacts, such as additional material costs, labor hours, or equipment expenses. By providing real time cost estimates, project managers can make informed decisions regarding the change. If the cost impact is too high, they may explore alternative solutions or negotiate with relevant parties. This kind of mobile based reporting not only streamlines the change management process but also enhances the precision of dynamic cost control, ultimately contributing to the successful delivery of construction projects within budget [13].

5.3. Case study analysis

5.3.1. Project background and implementation process

Take a large-scale infrastructure project as an example. This project was a crucial transportation related construction, aiming to improve regional connectivity. The initial plan was to construct a high-speed railway line across multiple regions, with a total length of over 300 kilometers.

The project kicked off with detailed pre construction planning. Surveyors spent months mapping the terrain, analyzing geological conditions, and identifying potential environmental impacts. Once the site-specific information was gathered, the design team started to develop the construction blueprints, taking into account various factors such as load bearing capacity, speed requirements, and safety standards.

During the implementation process, the project faced several challenges that led to change visas. For instance, unforeseen underground water sources were discovered in some sections, which required immediate adjustments to the foundation construction plan. This led to a change visa, altering the construction methods and materials. Another situation was when local residents raised concerns about the noise impact of the construction, resulting in additional requirements for noise reducing measures, thus causing another change visa.

The project team closely monitored these changes and their associated costs. They set up a real time cost tracking system that updated cost data daily. Key milestones in the implementation included the completion of the foundation work, the erection of bridge piers, and the laying of tracks. Each milestone was carefully reviewed to ensure that the project was on track in terms of both progress and cost control. This case clearly shows the practical application of change visa management and dynamic cost control in a large-scale infrastructure construction project.

5.3.2. Performance metrics and cost savings

The case study focuses on quantifiable performance metrics to demonstrate the effectiveness of change visa management and dynamic cost control. A key metric is the reduction in change processing time. In the project under study, an 18% decrease in change processing time was achieved. This was crucial as it minimized project delays. Swift processing of change visas ensured that any necessary adjustments to the construction plan could be implemented promptly, preventing idle time for construction teams and potential rework due to extended waiting periods.

Cost overrun mitigation is another vital performance metric. The project managed to mitigate cost overruns by 12%. This was accomplished through strict review and control of change visas. Each change was carefully evaluated for its necessity and cost implications. By doing so, unnecessary changes that could have inflated costs were avoided. For example, alternative solutions were explored to meet project requirements without incurring excessive expenses.

Improved audit compliance rates also signify effective management. A higher audit compliance rate indicates that the change visa management and cost control processes adhered to relevant regulations and internal policies. This not only reduces the risk of legal issues but also enhances the overall credibility of the project. These performance metrics and cost savings clearly illustrate the positive impact of effective change visa and dynamic cost control measures in the construction stage of construction projects.

6. Conclusion

In conclusion, the integration of dynamic cost control with systematic change visa management in the construction stage of construction projects has demonstrated remarkable transformative potential. Through this approach, significant efficiency gains have been achieved, such as streamlined decision making processes regarding change visas. This not only reduces unnecessary delays but also optimizes resource allocation, ensuring that projects are completed within the planned schedule.

Value preservation in project delivery is another crucial outcome. By closely monitoring and controlling costs in real time during the change process, potential cost overruns are effectively mitigated. This ensures that the final project cost aligns with the budget, safeguarding the economic viability of the project.

Looking ahead, future research could focus on AI enhanced change prediction. AI technologies, with their ability to analyze vast amounts of historical data, can potentially predict changes more accurately. This would enable project teams to anticipate and prepare for potential changes in advance, further enhancing cost control and project management.

Blockchain based audit trails also present an exciting area of exploration. The immutability and transparency of blockchain can provide a secure and reliable record of all change visas and cost related transactions. This would enhance accountability, streamline auditing processes, and reduce the risk of fraud, thereby contributing to more effective project management in the construction industry. Overall, these future research directions hold great promise for further improving the management of change visas and dynamic cost control in construction projects.

Disclosure statement

The author declares no conflict of interest.

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Research and Application of Building Engineering Intelligent Review System Based on BIM and Rule Engine

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Abstract: The research aimed to construct an intelligent review system for construction projects based on Building Information Modeling (BIM) and rule engines. By establishing a BIM data standard system and utilizing Structured Naming Language (SNL) to formalize review rules, combined with model visualization and scene recognition technology, a cloud native platform with automated review capabilities has been developed. The pilot application shows that the system can effectively improve the efficiency and accuracy of planning and construction drawing review, providing a feasible technical solution for digital engineering review.

Keywords: Building Information Modeling (BIM); Rule engine; Intelligent review

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1. Introduction

With the deepening implementation of the "14th Five Year Plan" for the development of the construction industry and the announcement of the list of pilot cities for intelligent construction by the Ministry of Housing and Urban Rural Development in 2022, promoting the digital transformation and intelligent upgrading of the construction industry has become a clear direction for industry development. The traditional construction project review mode highly relies on manual interpretation of two-dimensional drawings, which has problems such as low efficiency, inconsistent standard implementation, and easy omissions, making it difficult to meet the higher requirements of modern construction industry system for quality and efficiency. Building Information Modeling (BIM) technology, as an important carrier of engineering digitization, has provided the possibility for achieving automation and intelligence in the review process. However, achieving machine understandable and executable expression of normative provisions, and building a review system capable of automatic reasoning and recognition, remains the core technical challenge currently faced. Therefore, researching intelligent review systems based on BIM and rule engines has urgent practical significance for implementing national intelligent construction policies, improving engineering review efficiency, and ensuring engineering quality and safety.

2. Overall architecture design of BIM intelligent review system

2.1. System architecture design principles

The architecture design of this system follows the principles of cloud native and modularization, ensuring that the platform has high scalability, flexibility, and reliability. The system is centered around microservices, encapsulating core capabilities such as data management, model parsing, and rule engines as independent services to achieve loose coupling and on-demand deployment of services. Openness is an indispensable principle, and the system supports international common data formats such as IFC, and is committed to cloud based lossless parsing and integration of multi-source heterogeneous BIM models, breaking the dependence on specific modeling software. This is in line with the requirements for data integration and interoperability in the optimization of digital review processes for construction drawings [1]. In terms of technical architecture, knowledge graphs are used as the underlying storage and organization method for BIM data, revealing the complex relationships between components through semantic modeling, providing an efficient data query and relationship reasoning foundation for intelligent review. Security runs through the entire design process, with full process permission control and operational traceability of model data to ensure the integrity and immutability of data during circulation and review.

2.2. Division of system functional modules

The system is divided into seven core functional modules based on the intelligent review business process. The BIM data standard service module is responsible for maintaining unified classification codes, attribute sets, and delivery standards, providing benchmarks for model quality. The model parsing and conversion module undertakes the cloud based lightweight parsing and conversion tasks of multi format BIM models, and outputs unified structured data. The model visualization and rendering module provides lightweight browsing, interaction, and linkage functions for web-based 2D and 3D models. The review rule engine module is the intelligent core of the system. Based on structured SNL rule descriptions, it performs automatic compliance checks and logical reasoning. Its precise analysis and execution of professional provisions such as fire safety regulations are the key technical support for achieving efficient and accurate review [2]. The review scenario management module utilizes graph technology to achieve pre identification and tagging of review scenarios, improving the efficiency of rule matching and review. The review result management and reporting module visualizes, categorizes, and generates reports on the review results. The system integration and interface module provides a standardized channel for data exchange and business process integration between the platform and external systems, such as CIM platform, project management system.

3. BIM data standards and model processing techniques

3.1. Construction of BIM data standard system

The BIM data standard system is the cornerstone for ensuring information interoperability and automated review. The system is built around a unified component classification and coding rule, clarifying the identification and organizational logic of various model elements. The attribute parameter standard defines inherent information such as material and size of components, and extends the attributes that need to be filled in by the design end, standard attributes directly extracted from the model, and derived attributes obtained through geometric and business rule deepening calculations. The definition of these calculated attributes is crucial for achieving automated review of architectural design specifications [3]. The model geometry standard standardizes the geometric representation methods and spatial relationships of components, ensuring visual consistency and computational accuracy of the model. The data format and exchange standards have established an open data environment centered around

IFC, supporting cross platform, full lifecycle information lossless transmission. This comprehensive standard framework provides a unified data specification for model quality assessment, engineering quantity statistics, and full process collaboration, which is a prerequisite for achieving intelligent review.

3.2. Cloud parsing and storage technology for multi format models

Faced with multi-source heterogeneous BIM model data, cloud parsing technology is committed to achieving format generalization processing that is decoupled from the native modeling software environment. The core of this technology is to deeply parse the data structures and encoding methods of mainstream formats such as RVT and DGN, and convert them into a unified intermediate data format within the system. Synchronize the simplification and optimization of model data during the parsing process, and improve network transmission and parsing efficiency by removing redundant information, optimizing data organization and compression techniques. At the data storage level, the system breaks through the limitations of traditional relational databases or pure file storage, explores the lightweight and flat transformation of IFC standards, and innovatively adopts knowledge graph technology for the organization and management of BIM data. This graph-based storage maps components, attributes, and their complex relationships to nodes and edges, providing efficient support for semantic based complex queries, rapid extraction of sub models for business scenarios, and deep relational reasoning. To ensure the security and credibility of data during this process, distributed ledger technology can be introduced to authenticate key operations and enhance the credibility of review results, thereby greatly improving the flexibility, security, and intelligence level of data utilization [4].

4. Rule engine and intelligent review method

4.1. Structured expression of multiple review rules

4.1.1. Specification description method based on SNL

To achieve machine-readable and executable functionality, the review rules are formally described using Structured Naming Language (SNL). This method converts design specifications written in natural language into standardized computer statements, clearly defining the types of components, key attribute requirements, and spatial and logical relationships that must be satisfied between components in the model. For example, the review provisions for fire separation distance can be transformed into logical assertions that measure and compare the geometric positional attributes of specific component categories (such as walls, doors, and windows). This unified description format based on SNL provides precise and error free instruction input for the review rule engine, which is the core technical foundation for achieving a leap from manual interpretation to automated and intelligent review. Its purpose is to solve the efficiency bottleneck and subjective deviation problems caused by relying on manual item by item verification in the traditional review process, ensuring the consistency and ambiguity of machine understanding of normative provisions [5].

4.1.2. Construction and management of review rule library

The construction of the review rule library began with a systematic review of mandatory provisions and industry standards in stages such as reporting for construction and construction, and reviewing construction drawings. Collaborating with experts in the professional field and BIM engineers, the selected articles are translated and structured using SNL language to form an initial set of atomic rules. The rule library adopts a hierarchical classification architecture for management, which can be organized in multiple dimensions based on professional fields (such as architecture, structure, fire protection), applicable stages, and regulatory sources, supporting efficient retrieval and reuse of rules. The rule library management system provides version control, state management, and dependency analysis functions for rules, ensuring that relevant rules can be quickly located and iterated during specification updates, maintaining the timeliness and accuracy of the rule library. This systematic rule management mechanism is crucial for responding to dynamic updates of normative provisions and ensuring the authority and compliance of review criteria [6]. It is an institutional guarantee for the reliable operation and industry recognition of intelligent review systems, providing dynamic knowledge support for the continuous evolution of intelligent review.

4.2. Review the scene recognition and reasoning mechanism

4.2.1. Scene feature extraction and tagging

The foundation of reviewing scene recognition lies in transforming complex review articles into computable scene features. By deeply analyzing the semantics of the text, extracting the professional fields involved, target component types, key attribute constraints, and spatial or logical relationships between components, a feature triplet centered on "subject relationship object" is formed. These features define specific review contexts, such as "evacuation stairs–minimum net width–greater than or equal to the specified value". After uploading the model, the system scans and matches the BIM model based on a predefined scene feature classification system, identifies local parts of the model that match specific feature combinations, and automatically attaches corresponding scene labels to them. This tagging process logically aggregates originally scattered components based on review intent, laying the foundation for subsequent targeted and efficient rule execution. Its effectiveness has been verified in practical projects such as the Nanjing Construction Drawing BIM Intelligent Review System, significantly improving the automation level of review [7].

4.2.2. Model mapping and review reasoning

The effectiveness of scene recognition heavily relies on the graphical representation of BIM models. Model visualization transforms traditional BIM data into a semantic network consisting of "nodes" (representing component instances) and "edges" (representing relationships between components). This transformation explicitly expresses and stores complex relationships such as component properties, spatial topology, and system associations. In the review reasoning stage, the rule engine does not need to directly process the original geometric model, but operates on the labeled scene subgraphs. The engine traverses nodes and edges in the graph to verify whether their attributes meet the conditions specified by SNL rules, and uses graph query and inference algorithms to discover implicit associations and conflicts. For example, by analyzing the topological relationship between fire zones and evacuation routes, automatic inference of whether evacuation distances are compliant can help systematically identify and warn of complex spatial logic problems that are easily overlooked in traditional manual reviews [8]. This graph-based reasoning mechanism significantly enhances the ability and efficiency of reviewing complex spatial and logical relationships.

5. System implementation and pilot applications

5.1. Development of BIM intelligent review platform

5.1.1. Implementation of platform core function modules

The platform is based on a microservice architecture and integrates seven core functional modules to support the entire process of intelligent review. The data standard service module maintains component classification, coding, and attribute rules, providing a unified benchmark for model quality. The model parsing service realizes cloud conversion and lightweight processing of multi-source BIM formats, and outputs structured model data. The model rendering service provides online browsing and interaction capabilities for 2D and 3D models in a web environment. The rule engine service serves as the system brain, loading and executing structured review rules based on SNL language. The scenario management service utilizes knowledge graph technology to achieve automatic recognition and tagging of review scenarios. Review and analyze the coordination of various modules in the service, and perform specific compliance checks and conflict detection. The results reporting service visualizes the review results and generates structured review reports. Each module works together through standardized interfaces to form a complete automated review loop, marking a profound transformation of the construction drawing review mode from traditional manual led to intelligent and systematic direction [9].

5.1.2. Application of 2D and 3D graphic modeling linkage technology

To solve the problem of disconnection between 2D drawings and 3D models in traditional review, the platform has implemented deep 2D and 3D model linkage technology. This technology automatically extracts the type, position, and size information of components such as walls, doors, and windows in CAD drawings through drawing element recognition algorithms. Establish precise spatial correspondence between 2D graphics and 3D model components using coordinate mapping relationships. Reviewers can select specific elements on the 2D drawing, and the system automatically locates and highlights the corresponding model components in the 3D view, synchronously displaying all their attribute information. This technology not only greatly facilitates the consistency review of graphics and models, enabling the rapid detection and localization of design conflicts and expressions that do not match, but also provides an intuitive and efficient human-computer interaction interface for core review functions. This technology demonstrates significant advantages in dealing with specialized reviews involving complex spatial relationships, such as compliance verification of sponge city facility layout and vertical design. It can effectively assist reviewers in understanding design intent and verifying technical details, improving the accuracy and efficiency of the entire review process [10].

5.2. Pilot application and effect analysis

5.2.1. Pilot program for review of regulatory and construction applications

During the planning and application stage, the system conducted pilot applications for the issuance of construction project planning permits. The pilot focuses on automated verification of key planning indicators such as building area, building height, plot ratio, and green space ratio. The platform automatically extracts the geometric and attribute information of relevant components by parsing the BIM model submitted for construction, and performs indicator calculation and compliance comparison based on preset SNL rules. The application results show that the system can quickly and accurately complete the review of various planning and control indicators, transforming the large amount of repetitive work that originally relied on manual accounting into an automated process that can be completed in seconds. This not only significantly improves the efficiency of initial review of construction materials, reduces repeated modifications caused by human calculation errors, but also provides objective and quantitative technical review basis for planning and management departments, strengthening the scientific and standardized nature of planning and management.

5.2.2. Pilot project for construction model review

The pilot project for construction drawing review mainly focuses on compliance inspections with mandatory regulations such as fire safety, civil air defense, and structural safety. The platform has loaded a review rule library for local standards such as the “Design and Delivery Standards for Building Information Modeling”, which systematically reviews the integrity of BIM model components, design depth, and implementation of regulatory provisions during the construction phase. The pilot verified the effectiveness of the system in detecting common design issues such as integrity of fire compartments, insufficient evacuation width, and inadequate fire resistance limits of components. Through automated review, a large amount of basic and standardized specification clause inspection work can be efficiently completed, allowing reviewers to focus their energy on more complex engineering judgments and design optimization suggestions. This effectively enhances the comprehensiveness and accuracy of construction drawing review, providing a powerful technical tool for ensuring project quality and safety from the source.

5.3. System performance and economic benefit analysis

5.3.1. Achievement of main technical indicators

System performance is measured through a series of quantifiable technical indicators. In terms of model processing capability, the platform has successfully achieved cloud parsing and lightweight conversion of BIM models generated by mainstream software such as Revit and ArchiCAD, supporting smooth online browsing of GB level models. The rule engine has efficient reasoning ability and can complete rule matching and result output in seconds for typical review scenarios containing hundreds of components. The system supports concurrent user access and maintains response times in sub seconds, ensuring a collaborative review experience for multiple users. In terms of accuracy, the structured rule expression and graph-based reasoning mechanism based on SNL significantly improves the accuracy of the system's review of clearly defined normative provisions compared to traditional manual sampling, especially in the verification of spatial relationships and quantitative indicators, demonstrating stable and reliable performance.

5.3.2. Economic and social benefit evaluation

The application of this system has generated significant comprehensive benefits. At the economic level, automated review significantly reduces the time cost of manual verification of drawings and specifications, freeing reviewers from repetitive labor and focusing on higher value technical decisions, directly reducing the manpower investment and time cycle of project review. Early detection and correction of design errors have avoided rework and changes during the construction phase, resulting in significant indirect economic benefits. In terms of social benefits, the system has improved the standardization and transparency of the review process, enhanced the ability to control engineering quality, and helped prevent safety risks from the source. Its promotion and use have promoted the deep application of BIM technology and the digital transformation of the construction industry, providing key technical support for building a collaborative, efficient, and intelligent new construction model.

6. Summary

A set of intelligent review methods and technical systems based on BIM and rule engines have been systematically constructed to meet the practical needs of intelligent review in construction engineering. The research has established a system architecture centered on cloud native and openness, and developed BIM data standards covering component classification, attribute parameters, and data exchange, laying the foundation for information interoperability and automated review. By introducing SNL language to achieve structured description of review rules and combining knowledge graph technology for semantic storage and scene recognition of BIM models, the accuracy and efficiency of review reasoning have been effectively improved. On this basis, the BIM intelligent review platform developed integrates core functions such as multi format parsing, rule engine, and 2D/3D linkage, forming a complete review loop. The pilot application in stages such as planning and construction drawing review has shown that the system can significantly improve review efficiency and quality, reduce labor costs and error rates, and demonstrate good technical feasibility and application value. This research achievement provides a practical and feasible technical path and practical reference for promoting the intelligent transformation of construction project review, and has positive significance for promoting the digital development of the construction industry.

Disclosure statement

The author declares no conflict of interest.

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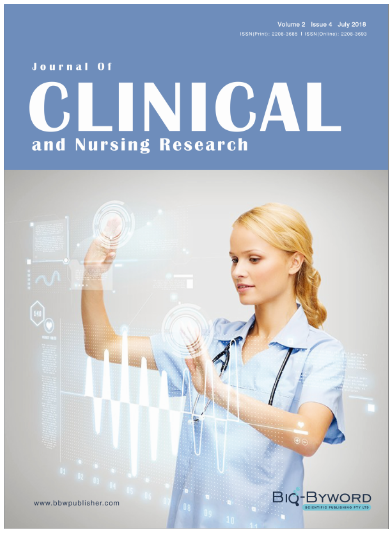

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