Research on Construction Progress Management and Critical Path Optimisation for Complex Structural Projects

Jinsong Hu

Anhui Poly Real Estate Development Co., Ltd., Hefei, Anhui, 230000, China

Keywords: Complex Structural Engineering; Construction Schedule Management; Critical Path Method (CPM); Schedule Optimization; BIM Technology

Abstract: Due to their massive scale, numerous construction processes, and complex interdisciplinary coordination, complex structural engineering projects often face high uncertainty and difficulty in construction schedule management. Effectively shortening project duration and improving resource utilization while ensuring engineering quality and safety has become a core issue in construction organization and project management. This paper investigates schedule management and critical path optimization for complex structural engineering projects. First, it analyzes the key characteristics and challenges of schedule management in such projects, highlighting the limitations of traditional methods in dynamic adjustments and multi-disciplinary coordination. Second, it explores the application mechanism of the Critical Path Method (CPM) in complex projects, proposing an optimization approach through adjusting task logical relationships, optimizing resource allocation, and implementing time-cost balancing strategies. Simultaneously, an intelligent dynamic progress monitoring and optimization framework is established by integrating information technologies such as BIM, big data, and artificial intelligence. Finally, case studies validate the feasibility and effectiveness of key path optimization. Results demonstrate that the implementation of optimization strategies significantly shortens project duration, enhances the rationality of construction resource allocation, and markedly improves overall progress control. This research provides theoretical support and practical guidance for the scientific management and intelligent optimization of construction progress in complex structural engineering.

1. Introduction

As construction scales continue to expand and structural forms grow increasingly complex, the demand for scientific management of construction schedules in engineering projects has become more urgent [1]. Complex structural projects typically feature massive scale, intricate work processes, frequent interdisciplinary coordination, and extended construction cycles [2]. Their schedule management not only impacts project delivery timelines but also directly influences investment control and quality/safety outcomes [3]. However, in actual construction, schedule management is often constrained by high process coupling, resource coordination challenges, and external environmental uncertainties [4]. This frequently leads to schedule delays, project setbacks, and resource wastage [5]. How to effectively optimize construction schedules, shorten critical durations, and enhance construction efficiency while ensuring quality and safety has become a core challenge requiring urgent resolution in engineering management [6]. Although existing schedule management methods have developed a relatively systematic theoretical framework—with the Critical Path Method (CPM) widely applied in construction organization design and schedule control—they still exhibit limitations such as insufficient flexibility and limited dynamic adjustment capabilities when applied to complex structural engineering projects [7]. In recent years, driven by advancements in information and intelligent technologies such as BIM, big data, and artificial intelligence, research and practice in schedule optimization have emerged with new trends. This paper aims to explore application methods for critical path optimization by summarizing the characteristics and challenges of schedule management in complex structural engineering. It proposes more efficient approaches to schedule control and optimization by integrating information technology tools, thereby providing valuable insights for the scientific management of complex structural projects.

  DOI: 10.25236/icacel.2025.110

2. Characteristics and Challenges of Schedule Management in Complex Structural Engineering

As one of the most representative types in the construction industry, complex structural engineering projects often involve large scale, innovative structures, and intensive interdisciplinary collaboration[8]. Their schedule management exhibits distinct characteristics compared to conventional projects[9]. First, structural complexity directly leads to highly intertwined construction processes[10]. Such projects frequently encompass multiple construction phases—including steel structures, concrete structures, MEP installations, and curtain wall finishes—each governed by strict logical sequences and high interdependencies. Delays in any critical process can trigger chain reactions, causing overall schedule setbacks. Secondly, the coordination of multiple disciplines and trades imposes heightened demands on construction organization. Different specialized teams frequently work in overlapping areas within the same construction space. Without effective progress coordination mechanisms, conflicts and resource wastage are likely to occur, thereby reducing overall efficiency. Earliest Start Time (EST) of an activity

$$EST_i = \max_{j \in P(i)} \{EFT_j\} \qquad (1)$$

Additionally, complex structural projects are often subject to extended construction cycles and challenging site conditions, making them more susceptible to external uncertainties affecting progress. For instance, fluctuations in the material supply chain, changes in weather conditions, and policy or safety control requirements can all disrupt the execution of schedule plans, increasing the difficulty of progress control. At the same time, traditional progress management methods reveal limitations in complex environments. Common schedule planning and control methods are often based on static plans, lacking dynamic adjustment and real-time monitoring capabilities, and unable to respond promptly to unexpected resource bottlenecks or schedule deviations during construction.

In summary, schedule management for complex structural engineering construction presents challenges characterized by strong process dependencies, significant organizational coordination difficulties, high external uncertainty, and the inadequate adaptability of traditional methods. Only by accurately identifying these issues and introducing scientifically sound schedule optimization and dynamic management techniques can the timely and high-quality completion of projects be effectively ensured.

3. Application of Critical Path Optimization in Construction Schedule Management

In managing schedules for complex structural engineering projects, the Critical Path Method (CPM) is widely applied in planning and schedule control due to its ability to reveal logical relationships between work processes and identify critical time-determining factors. However, relying solely on traditional CPM analysis often fails to meet the flexibility and dynamic adjustment requirements of complex projects. Therefore, systematic enhancements are needed in method application, optimization strategies, and technical support. On one hand, a deep understanding of CPM principles and applicability is essential to ensure the scientific rigor and feasibility of schedule plans. On the other hand, path optimization effectiveness should be enhanced by adjusting task relationships, optimizing resource allocation, and balancing time and cost. Concurrently, leveraging information and intelligent technologies such as BIM, big data, and artificial intelligence provides technical support for dynamic adjustment and optimization of the critical path. These three aspects collectively form the core content of critical path optimization in complex structural engineering. Earliest Finish Time (EFT)

$$EFT_i = EST_i + d_i \qquad (2)$$

3.1 Principles and Applicability of the Critical Path Method (CPM)

The Critical Path Method (CPM) is one of the most widely applied techniques in project schedule management. Its core concept involves identifying the logical relationships between project activities to calculate the critical path that determines the overall project duration. The critical path refers to the longest sequence of interconnected tasks with zero float, directly determining the project's earliest possible completion date. By identifying and controlling this path, managers can pinpoint key factors affecting progress, enabling more targeted planning and schedule monitoring, showed in Figure 1:

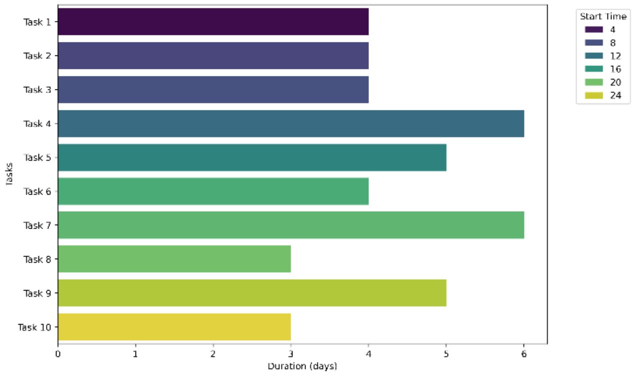

Figure 1 Progress distribution

In complex structural engineering, CPM's fundamental principle manifests as the systematic decomposition and logical sequencing of construction activities. By establishing a network schedule diagram, the sequential relationships, durations, and dependency conditions of each process are represented through nodes and arrows. Forward and backward calculations then determine the earliest start time, latest finish time, and total float, ultimately identifying the critical path that dictates the project schedule. This method not only provides a clear logical framework for construction organization but also intuitively reveals the importance of critical processes during the planning phase. Latest Finish Time (LFT)

$$LFT_i = \min_{k \in S(i)} \{LST_k\} \qquad (3)$$

The applicability of the Critical Path Method in complex structural engineering primarily manifests in the systematic and controllable nature of schedule management. On one hand, it provides project managers with quantitative decision-making support, enabling more scientific and rational resource allocation, task sequencing, and schedule control. On the other hand, identifying the critical path allows project teams to concentrate limited management resources on key stages, thereby enhancing management efficiency while ensuring overall progress. This is particularly crucial for complex structural projects involving intricate processes and high coordination demands.

However, the CPM also has certain limitations in practical application. Traditional CPM is often based on static assumptions—that is, the duration and logical relationships of all processes remain unchanged throughout the planning period. This approach lacks sensitivity to dynamic changes and uncertainties during construction. In complex structural projects, construction environments are highly variable, and resource supply is susceptible to external influences, meaning the critical path can shift at any time. Therefore, applying CPM to complex projects must be combined with dynamic adjustments and information technology to maximize its effectiveness.

3.2 Strategies and Methods for Critical Path Optimization

In complex structural engineering, optimizing the critical path is central to construction schedule management. Since tasks on the critical path directly determine the project's overall duration, rational adjustments and optimizations can significantly enhance overall schedule control. The fundamental approach involves refining task logical relationships, optimizing resource allocation, and balancing time and cost to create a more scientific and efficient construction plan, thereby shortening the schedule and improving construction efficiency. Latest Start Time (LST)

$$LST_i = LFT_i - d_i \qquad (4)$$

First, regarding task logical relationships, optimization focuses on reasonably compressing the duration of critical tasks and increasing the degree of parallelism between tasks. While ensuring quality and safety, methods such as task subdivision, assembly line operations, and overlapping construction can be employed to reduce constraints on critical tasks imposed by non-critical ones, thereby avoiding schedule delays caused by unreasonable logical relationships. Additionally, technical measures such as prefabricated components or mechanized construction techniques can accelerate critical process progress, effectively shortening the overall project timeline.

Second, resource allocation optimization prioritizes directing limited construction resources to critical path processes. By rationally deploying labor, machinery, and materials, delays in critical processes due to resource shortages are prevented. Simultaneously, to address potential resource bottlenecks during construction, dynamic scheduling methods can be introduced. These allow real-time adjustments to resource allocation plans based on site conditions, ensuring priority support for critical processes. This not only facilitates smooth progress along the critical path but also enhances overall resource utilization efficiency.

Third, balancing time and cost requires comprehensive consideration of the relationship between schedule compression and economic investment. Typically, shortening the schedule often leads to increased costs, such as requiring additional labor input or adopting more advanced construction techniques. Therefore, during critical path optimization, a time-cost balance analysis should be employed to identify the optimal combination of schedule and cost. This ensures the achievement of schedule targets while controlling project costs, avoiding the pitfall of blindly pursuing schedule compression at the expense of cost control. Total Float (TF) of an activity

$$TF_i = LST_i - EST_i = LFT_i - EFT_i \qquad (5)$$

In summary, critical path optimization requires integrated strategies across three dimensions: process logic, resource allocation, and time-cost balancing. Only through coordinated efforts across these areas can the scientific management and efficient optimization of construction schedules for complex structural projects be achieved.

3.3 The Supporting Role of Information and Intelligent Technologies

As the level of information and intelligent technologies in the construction industry continues to advance, traditional critical path management methods are undergoing deep integration with modern technological approaches, thereby providing new support for optimizing the construction schedules of complex structural projects. The application of information and intelligent technologies enables more efficient and precise identification and adjustment of critical paths, while also creating conditions for dynamic monitoring of the construction process and scientific decision-making.

First, Building Information Modeling (BIM) plays a particularly prominent role in optimizing critical paths. BIM technology enables three-dimensional visualization and information integration throughout the entire construction process, helping managers intuitively grasp the logical relationships and spatial conflicts between various work processes. Leveraging BIM's progress simulation capabilities, multiple scheme comparisons and dynamic simulations can be conducted to identify potential issues in advance and optimize critical path adjustments, thereby enhancing the scientific rigor and feasibility of schedules.

Second, big data technology provides robust data support for schedule management. Real-time collection and analysis of on-site progress data, resource utilization, and external environmental information enable managers to promptly detect schedule deviations and predict potential changes in the critical path. Trend analysis and risk warning mechanisms based on big data transform critical path optimization from static calculations to rapid responses to dynamic changes in complex environments, showed in Figure 2:

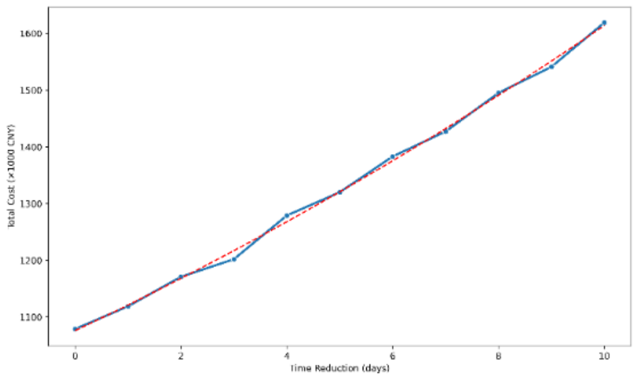

Figure 2 Time-Cost Trade-off Curve

Third, the integration of artificial intelligence and intelligent scheduling systems propels schedule optimization into an intelligent phase. Machine learning algorithms enable the mining of historical project data to generate more accurate duration prediction models for work processes. Intelligent scheduling systems automatically generate optimized construction plans under multiple constraints, achieving optimal resource allocation and real-time schedule adjustments. Furthermore, the application of IoT and sensor technologies enables real-time monitoring of construction processes, providing reliable data support for dynamic critical path optimization.

Overall, the integration of information and intelligent technologies has significantly expanded the application scope of the Critical Path Method. It not only enhances the formulation and optimization of schedule plans but also strengthens the dynamism and foresight of schedule control. In the future, with the continuous advancement of technologies such as BIM, big data, artificial intelligence, and digital twins, schedule management for complex structural engineering projects will gradually achieve intelligence and automation, providing a more robust technological foundation for critical path optimization.

4. Case Study and Optimization Effect Evaluation

To validate the practical effectiveness of critical path optimization in managing complex structural construction schedules, this paper examines a large-scale public building project. With a floor area exceeding 200,000 square meters and a complex structural composition—including steel structures, concrete structures, and MEP installations—the project originally planned a 36-month construction cycle. Characterized by frequent work overlaps and substantial resource demands, it faced typical challenges of complex structural projects: high schedule control difficulty and frequent plan adjustments.

During the schedule planning phase, the project team systematically decomposed and logically sequenced construction tasks using the Critical Path Method (CPM), preliminarily identifying several critical processes including main structure construction, steel structure installation, integrated MEP piping and ductwork layout, and curtain wall engineering. By establishing a network schedule and performing forward and backward calculations, the critical path and its duration were determined. However, during construction, delays occurred in some critical processes due to resource constraints and external conditions, increasing overall schedule risks and necessitating urgent optimization of progress management. Time–Cost Trade-off Objective Function

$$\min Z=\sum_{i=1}^{n}\left(C_i+\Delta C_i\right) \quad \text{s.t.} \quad T \le T_{target} \qquad (6)$$

To address these issues, the project team implemented multiple optimization measures: First, adjusting process logical relationships by converting some sequential tasks to parallel operations. For example, inserting certain MEP pre-installation works before the main structure was fully completed to compress the schedule; Second, dynamically allocated resources to increase manpower and machinery for critical processes, ensuring their timely completion. Third, integrated time-cost balancing analysis to introduce nighttime and mechanized construction methods when necessary, achieving an optimal balance between schedule compression and cost control. Concurrently, BIM technology was employed for dynamic simulation and visualization of the critical path, enabling real-time progress monitoring and multi-scenario comparisons.

The optimized critical path analysis results indicate that the project's total duration was reduced from the original 36 months to 32 months, representing an 11.1% reduction. Furthermore, resource utilization during construction significantly improved, with more rational material supply and labor scheduling, effectively reducing on-site conflicts and rework. The effectiveness evaluation confirms that the key path optimization strategy holds significant application value in complex structural engineering projects. It not only shortens the construction period but also enhances construction organization efficiency, providing valuable practical experience for schedule management in similar projects.

5. Conclusion

Due to their large scale, numerous processes, and frequent interdisciplinary coordination, construction schedule management remains a critical factor in the success of complex structural engineering projects. This paper examines the characteristics and challenges of schedule management in complex structural projects, systematically analyzes the application mechanisms of the Critical Path Method in construction organization and plan control, and proposes a Critical Path Optimization Strategy addressing three dimensions: adjusting process logical relationships, optimizing resource allocation, and balancing time-cost tradeoffs. By integrating information technologies such as BIM, big data, and artificial intelligence, an intelligent dynamic schedule optimization framework is established. Case studies validate that key path optimization effectively shortens project duration, enhances resource utilization, and elevates schedule control capabilities, demonstrating significant practical value.

Research indicates that the core of schedule management lies not only in static identification of critical paths but also in timely responses to dynamic changes and scientific adjustments. Looking ahead, with the advancement of smart construction and digitalized building practices, key path optimization will progressively evolve toward intelligent and automated stages, further enhancing the scientific rigor and foresight of schedule management. The findings of this study provide theoretical support and practical guidance for schedule management in complex structural engineering construction, contributing positively to advancing the construction industry toward greater efficiency, intelligence, and lean practices.

References

[1] Wang L, Zhou G, Xu Y, et al. An effective artificial bee colony algorithm for the flexible job-shop scheduling problem[J]. International Journal of Advanced Manufacturing Technology, 2012, 60(1-4):303-315.

[2] Hu Y, Ding Y, Hao K, et al. An immune orthogonal learning particle swarm optimisation algorithm for routing recovery of wireless sensor networks with mobile sink[J]. International journal of systems science, 2014, 45(1-3):337-350.

[3] Waanders F, Visser F W, Gans R O B. Current concepts in the management of diabetic nephropathy[J]. Netherlands Journal of Medicine, 2013, 71(9):448-458.

[4] Chen C L. A 2.37-Gb/s 284.8 mW Rate-Compatible (491,3,6) LDPC-CC Decoder[J]. IEEE Journal of Solid-State Circuits, 2012, 47(4):817-831.

[5] Khardi S. Aircraft Shortest and Fastest Continuous Descent Approach Development[J]. Journal of Aircraft, 2012, 49(6):1931-1939.

[6] Seebacher F, Little A G, James R S. Skeletal muscle contractile function predicts activity and behaviour in zebrafish[J]. Journal of Experimental Biology, 2015, 218(24):3878.

[7] Yaobin S, Weiyong L, Changchun H, et al. Numerical Simulation of the Influence of Natural Fractures on Hydraulic Fracture Propagation[J]. Geofluids, 2020, 2020(5):1-12.

[8] Liu L, Li B, Qi B, et al. Survivability optimisation of communication network for demand response in source-grid- load system[J]. IET Communications, 2020, 14(17):2972-2980.

[9] Conceptual design of a compact helical fusion reactor FFHR-c1 for the early demonstration of year-long electric power generation[J]. Nuclear Fusion, 2019, 59(7):076030.

[10] Brucker A D, Brügger, Lukas, Wolff B. Formal firewall conformance testing: an application of test and proof techniques[J]. Software Testing Verification & Reliability, 2015, 25(1):34-71.