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

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Abstract: Because of their large-scale, many construction processes and multi-disciplinary coordination, complex structural engineering projects usually have high uncertainty and difficulty in construction schedule management. While ensuring engineering quality and safety, reasonable shortening of project duration and optimizing resource allocation, utilization rate has become a major problem in construction organization and project management. It is a paper which following the sustainable develop upgrading structural engineering projects schedule management and optimizing critical path. Firstly, it discusses fundamental attributes and challenges of schedule management in these projects, as well as the deficiencies of traditional techniques when dealing with dynamic re-adjustments and cross-disciplinary co-ordination. Second, the question of how to apply the Critical Path Method (CPM) in more specific complex project, which optimizes through changing task logic relations; optimizing resource allocation; and adopting time-cost balancing strategy. The second sub-article utilizes advanced information technologies including BIM, big data, and artificial intelligence to build an intelligent dynamic progress monitoring and optimization framework. Finally, case studies demonstrate the advantages and efficiency of doing key path optimization. The results show that the implementation of optimization strategies can significantly reduce project duration, enhance the rational allocation of construction resources and effectively improve overall progress control. The research results of this study can provide theoretical reference and practical guidance on the scientific management and intelligent optimization of construction progress for complex structural engineering.

1. Introduction

With the continuous expansion of construction scales and the diversification of structural forms, scientific management in engineering project schedule has become imperative [1]. Large-scale, complicated working flows, frequent interprofessional coordination and long construction period [2]. The way they manage the schedule not only directly affects the schedule delivery of a project but also will indirectly affect investment control and quality/safety outputs [3]. However, in actual construction, schedule management is often limited by high process coupling and resource coordination problems as well as external environmental uncertainty [4]. This often results in schedule overruns, delayed projects and wasted resources [5]. Efficient scheduling of engineering facilities to minimize critical times and improve construction efficiency while maintaining quality safety has becoming the core technical challenge that needs immediate solution in Engineering Management [6]. Although existing schedule management methods have established a relatively systematic theoretical framework, for example, the CPM has been widely used in construction organization design and schedule control; however, it still has many limitations when used in complex structure engineering projects [7]. Over the past few years, new trends in schedule optimization research and practice have emerged as a result of advances in information and intelligent technologies such as BIM, big data, and artificial intelligence. By summarizing the characteristics and problems of schedule management in complex structural engineering, this paper intends to explore application methods in critical path optimization. This paper suggests to provide valuable references for the scientific and technological management of complex structural projects by integrating information technology tools into more efficient scheduling control and optimization methods.

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

Complex structural engineering projects are one of the most representative types of projects in the construction industry, involving large scale and innovative structures, as well as intensive interdisciplinary collaboration [8]. The way they manage schedule, is quite different from the traditional projects [9]. First, structural complexity directly results in heavily interlinked construction processes [10]. Projects of such magnitude often has multiple construction phases, each consisting on steel structures, concrete structures, MEP installations and curtain wall finishes, with logical sequence and interdependencies never been so critical. Any delays during a critical process may cause chain reactions that affects overall schedules. Secondly, the involvement of more disciplines and trades increases organization demand for construction. Distinct specialized groups often operate in adjacent zones of the same construction space. When there are no effective mechanisms in place to coordinate progress, conflicts will occur, resources will be wasted and overall efficiency will decrease. Earliest Start Time (EST) of an activity

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

Lastly, complex structural projects typically represent longer construction cycles on challenging sites and the risk of external uncertainties that affect progress. However, the execution of schedule plans is always affected by changes outside of original plans which may disrupt progress control: E.g., the fluctuations in material supply chain and external weather conditions and policy or safety control requirements. Meanwhile, conventional approaches to managing progress don’t scale as well in complex environments. Most schedule planning and control methods rely on static plans, fail to adjust dynamically, lack real-time monitoring capabilities, and are incapable of quickly responding to unexpected resource bottlenecks or scheduling deviations during construction.

Scheduling management for complex structural engineering construction is manifested by strong process tie, greater organization coordination difficulty, drastic external environment uncertainty and poor adaptability of methods. Timely and high- quality completion of projects can only be guaranteed by correctly identifying these problems and implementing scientifically based schedule optimization and dynamic management methods.

3. Application of Critical Path Optimization in Construction Schedule Management

The CPM of the schedule is used widely in the planning and schedule control for complex structural engineering projects, primarily because it allows to establish logical relationships between work processes and determine critical time-limiting factors. Nevertheless, a restriction of traditional CPM analysis is that it is not applicable to all aspects used for complex projects where dynamic adjustment and flexibility are indispensable. Hence application of methods, strategies for optimization and technical support need to be improved systematically. A deep understanding of the CPM principles and applicational relevance is a must on one hand to achieve better scientific rigor and completeness in schedule plans. However, the path optimization performance was strengthened through various strategies such as optimizing task relationships and resource allocation and balancing time and cost. At the same time, utilizing information and intelligent technologies, like BIM, big data, artificial intelligence et al, gives technical support for dynamic adjustment and optimization to critical path. Together, these three elements are the essence of critical path optimization in complex structure engineering. Earliest Finish Time (EFT)

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

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

One of the most widely used techniques in project schedule management is Critical Path Method (CPM). It is based on how understanding the logical relationships between activities of the project may be used to compute the critical path, which determines the project length. The critical path is the longest chain of dependent activities which have zero float that defines the earliest possible finish date for a project. By identifying and controlling this path, managers can pinpoint key factors affecting progress, enabling more targeted planning and schedule monitoring ,showed in Figure 1 :

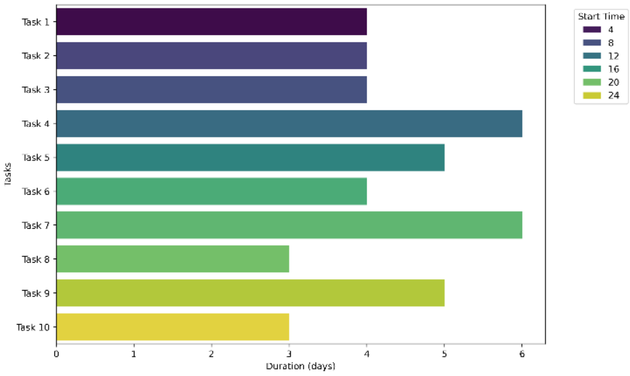

Figure 1 Progress distribution

CPM's underlying philosophy is exemplified in advanced structural engineering by the methodical breakdown and sequential arrangement of building tasks. That is, through the network schedule chart to show the process of each sequential relationship and its corresponding time between processes, dependency conditions showing nodes and arrows. Then, forward and backward calculations provide the earliest start time, latest finish time and total float, which helps identify the critical path that governs the project's scheduling. Not only does this not only offer a clear and logically provide information on how to organize the construction, but it also naturally shows us what we need to focus on in the planning process. Latest Finish Time (LFT)

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

The provisioning of the Critical Path Method finds its most relevant form of application in the facsimile governments of complex structural engineering, whereby scope management avails a systematic and controlled approach to schedule management. It offers quantitative decision-making support for project managers, which helps them allocate resources in a more scientific and reasonable way, carry out task sequencing and control the schedule. In contrast, distinguishing between the critical and noncritical paths enables project teams to focus scarce management resources on key stages: this improves management throughput with an eye towards overall progress. That is especially important for structural projects which are multi-faceted and highly coordinated.

Besides, there are some limitations associated with the CPM too as far as real-time application is concerned. Conventional CPM is generally grounded in static assumptions — meaning the timings and logical relations for all processes do not change during the time frame of interest. This method is not sensitive to changes and uncertainties during construction. Construction environments have a high degree of variance, external factors can impact resource availability and the critical path can change at any moment in complex structural projects. This means that, with complex projects, the application of CPM must be integrated within a dynamic environment by using information technology.

3.2 Strategies and Methods for Critical Path Optimization

In complex structural engineering, we find a hint of construction schedule management around the critical path. As the tasks on the critical path control the overall project duration, rational adjustments and optimizations can improve overall schedule control greatly. In this capability, both the logical relationship of tasks and related resource allocation such as time and cost are optimized to further provide a more scientific plan dedicated to shorten construction period and improve overall construction efficiency. Latest Start Time (LST)

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

First, we examine the logical correlation of tasks as optimization aims to reasonably shorten the critical path and improve parallelism between several tasks. It can reduce the constraints on critical tasks imposed by non-critical ones, and avoid the unreasonable logical relationship leading to schedule delay in from the other direction: while maintaining quality and safety. Task subdivision or assembly line operations, as well as overlapping construction, dynamic adjustment of tasks according to available technology and periodare methods that can be used under this situation. Moreover, prefabricated elements and mechanized construction solutions as part of technical measures can accelerate progress in a sensitive process which will help to save time between critical points of the project.

Secondly, optimization of resource allocation focuses on allocating limited construction resources to critical path processes. Resource shortages hinder critical processes, which are prevented by rational deployment of labour, machine and material. Also, dynamic scheduling methods can be applied to mitigate potential bottlenecks in resource during construction. This enables adaptations to resource allocation plans in real time according to site conditions and ensures that critical processes get top priority for support. This allows the critical path to progress smoothly throughout and makes higher efficient use of overall resources.

Third, to balance time and cost, we need to comprehensively consider the relationship between schedule compression and economic investment. Most often, shortening a schedule is an expensive endeavor that requires more labor force to get the job done or implement proven advanced construction techniques. Hence, time-cost balance analysis should be used for analysing critical path optimization to find suitable configuration between schedule and cost. This allows for the schedule targets to be met while maintaining control of project costs, rather than pursuing an approach that drives schedule slip based purely upon a desire to compressing the programs without regard to cost control. Total Float (TF) of an activity

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

The integration of these 3 dimensions; process logic optimization, resource allocation and time-cost balancing form the framework for critical path optimization. And only these three propositions can achieve complex structural project scientific management and efficient construction schedule optimization.

3.3 The Supporting Role of Information and Intelligent Technologies

With the continuous improvement of information level and intelligence technology in construction industry, classical critical path management method is deeply combined with modern technical method, which promotes new supports for optimal construction period in complex structure projects. The outstanding technologies of information and intelligent application may lead to more accurate identification and adjustment of critical path, as well as the conditions for dynamic monitoring of construction process and scientific decision.

First, Building Information Modeling (BIM) in the optimization of critical paths. Building Information Modeling (BIM) is a project geometric data-based technology with the capacity for deep integration and 3D display of information in the construction process with BIM seamlessly integrates coordinate points, dimensions, quantities and other key references to intuitively depict the logical relationships between various work processes as well as potential spatial conflicts. By utilizing BIM's progress simulation, it is possible to compare multiple schemes or perform dynamic simulations to identify potential problems in advance, optimize the adjustment of the critical path, improve the scientific nature and feasibility of schedules.

Secondly, big data technology also supplies strong data support for schedule management. Managers can detect schedule deviations in time and predict critical path shifts through real-time collection and analysis of on-site data (e.g., actual project progress), resource utilization, external environmental changes, etc. 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 :

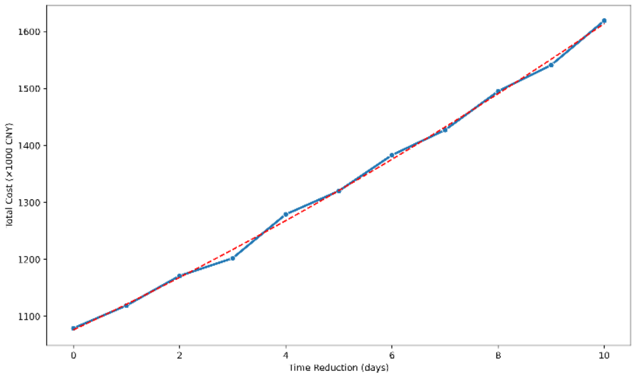

Figure 2 Time-Cost Trade-off Curve

In the third aspect, combining artificial intelligence with intelligent scheduling systems advances the state of schedule optimization into an intelligent phase. By analyzing past project data with machine learning algorithms, we can create better models for predicting the duration of work processes. Efficient planning is achieved by intelligent scheduling systems that prima facie deliver optimized construction plans under various constraints, granting optimal resource allocation and real-time adjustments to the schedule. In addition, the sensor technologies and IoT applications can monitor construction process in real-time for quality management, which provides reliable data support for dynamic critical path optimization.

The connection of data and smart technologies has greatly advanced the application range of the Critical Path Method. It adds not only better formulation and optimization of schedule plans, but also more dynamic and predictive regime of schedule control. With the continuous evolution of BIM, big data, artificial intelligence and digital twins and other technologies in the future, schedule management for complex structural engineering projects will gradually achieve intelligence automation, further solidifying a technological guarantee for critical path optimization.

4. Case Study and Optimization Effect Evaluation

This study investigates the effectiveness of a critical path optimization in an actual complex structural construction scheduling for a large-scale public building project. The project, which has a floor area of more than 200,000 square meters and involves steel structures, concrete structures, and MEP installations with complex structural composition (Multiple system Interactions) originally structured the construction cycle into 36 months. Typical features of complex building works are plenty of overlaps in work and high resource needs, which were evident in this project as well: schedule control was difficult and adjustments to the plan were frequent.

In the schedule planning stage, project personnel conducted systematic decomposition and logical sequencing of construction tasks through the Critical Path Method (CPM), initially determining a number of critical processes such as main structure construction, steel structure installation, integrated MEP piping and ductwork layout, curtain wall engineering. Using network scheduling and calculations in forward and backward manner defined the critical path. During construction, however, various important processes have experienced delays due to limited resources and external conditions resulting in increased schedule risks and the need for urgent optimization of progress management. Time–Cost Trade-off Objective Function

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

The project team took a number of positive measures to solve the above problems: First, it adjusted the logical relationship of process and converted some serial work into parallel stages. Such as inserting MEP certain pre-installation in advance as a move of the main structure did not finish, squeezing schedule; Second, according to the dynamically assigned resources, increase manpower and machinery for the key processes to ensure that they are completed on time. 1. 2. Integrated time-cost balancing analysis to appropriately introduce nighttime and mechanized construction methods in accordance with the conditions, so as to achieve an optimal balance between schedule compressing and cost controlling. Meanwhile, the use of BIM technology for dynamic simulation and visualization of critical path facilitated real-time progress tracking and multi-scenario comparison.

Optimized critical path analysis results show that the total project duration was reduced from 36 months to 32 months (a reduction of 11.1%). In addition, the resource utilization in construction was greatly improved, with a more reasonable material supply and labor’s time schedule, helping to reduce on-site conflicts and rework. The results of the effectiveness evaluation demonstrate that the proposed key path optimization strategy has considerable application value in complex structural engineering projects. It has not only significantly shortened the construction period but also improved the efficiency of construction organization, which is an important practical foundation for schedule management of similar projects.

5. Conclusion

The management of construction schedules is still one of the decisive factors in the success of complex structural engineering projects owing to their large scale, numerous processes, and frequent cross-discipline coordination. The composition and features of the schedule management in complex structural projects are reviewed, an analytical system is established for applications on Critical Path Method based construction organization and plan control, a Critical Path Optimization Strategy is proposed from three dimensions: adjusting process logical relationships; optimizing resource allocation and time-cost balance. An intelligent dynamic schedule optimization framework was developed by integrating information technologies including BIM, big data and artificial intelligence. Case studies confirm that the use of key path optimization leads to project completion in a shorter duration, better resource utilization, and improved schedule control capabilities - all demonstrating high practical value.

In fact, scientific adjustment and response to dynamic changes are crucial principles of schedule management. In the future, as construction is equipped with the intelligentization and digitalization of building practices, major path optimization will gradually develop from manual stage to intelligent and automated stages, making schedule management more scientific and forward-looking. This study should ideally be added to the research that provides both theoretical basis and practical guidance for schedule management in complex structural engineering construction, and make a positive contribution to the construction industry efficiency, intelligence and lean development.

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