International Journal for Housing Science and Its Applications
Publish August 10, 2025. Volume 46, Issue 4 Pages 1408-1422

https://doi.org/10.70517/ijhsa464128

Cross-application of combinatorial design theory in modular bridge construction schedule optimization

Jiang Li[1,*], Liang Luo[1], Xiaoqiang Ding[1] and Dakai Yuan[1]
[1] CCCC First Highway Engineering Co., Ltd. Fifth Engineering Co., Ltd, Beijing, 100000, China
Corresponding authors: (e-mail: Lijiangce@163.com).

Abstract Modular bridge construction projects face complex schedule management and optimization challenges, and traditional schedule control methods are often difficult to meet the actual needs. This paper proposes a combined design theory based on the critical path earned value method and Monte Carlo simulation method to optimize the progress of modular bridge construction. This paper takes a bridge construction project at a certain location in Village A as the research object, and introduces the critical path method on the basis of the traditional earned value method, so that the earned value method can more accurately reflect the different impacts of each critical work on the schedule. Then the mathematical characteristic solution is derived through Monte Carlo simulation, which more accurately gives the cumulative probability of completion of the modular bridge construction project and achieves the purpose of quantitative evaluation of the schedule. The critical path earned value method in this paper digs out the targeted reasons for cost deviation, and shortens the project duration by increasing the direct cost of the project several times, so that the cumulative probability of completion of the modular bridge construction project reaches 90.458%. It shows that the combination design theory in this paper is beneficial for the company to improve cost control in modular bridge construction projects.

Index Terms Monte Carlo simulation method, critical path earned value method, cumulative probability of completion, bridge construction schedule

I. Introduction

With the continuous development of modern construction technology, modular building has gradually emerged as an emerging form of construction. The concept of modular building first appeared in the 1960s, at first it was mainly used to solve the construction needs of military bases, field sites and other special places, with the continuous innovation of technology and the expansion of the scope of application, modular building has gradually penetrated into various fields such as health care, housing, bridges and so on [1]-[4]. Among them, modular bridge construction adopts factory production to decompose the construction process into a series of standardized modules, which are modularly designed and prefabricated, and then transported to the site to be assembled [5], [6]. Through the modular bridge construction technology, the bridge is divided into multiple modules for design and production, and each module is relatively independent, which is easy to manufacture and transport, and can effectively improve the construction quality, speed up the construction speed, reduce the consumption of resources and energy, and carbon emissions. And because the connection between the modules adopts a detachable design, once a module of the bridge is broken or needs maintenance, the corresponding module can be replaced or repaired, which greatly reduces the difficulty and cost of maintenance work [7]-[10]. However, on the one hand, the production and transportation of modules delay the bridge construction schedule and increase the cost due to factors such as production delays and the volatility of vehicle scheduling requirements [11], [12]. On the other hand, due to the differences in the scale and type of bridges, the progress of modular construction varies, and the larger the scale, the more modules, the assembly sequence is complex and diverse, and the construction progress needs to be optimized [13]-[15]. The theory of combinatorial design is studied by combining different elements in the target project in order to obtain the optimal combinatorial architecture that the target project has, which improves a new idea for the optimization of the construction schedule of modularization [16].

To address the shortcomings of the traditional earned value method in the application of modular bridge construction projects, this study proposes a critical path-based earned value construction management method, which focuses on the different degrees of influence of critical work on modular bridge construction projects, and introduces the parameter critical ratio as an indicator. A Monte Carlo simulation method is used to measure the uncertainty of the modular bridge construction schedule, which is applied to define the hypothetical variables, and then the computer is used to simulate the duration of each activity in the modular bridge construction project. The possible scenarios are also analyzed statistically to obtain the range of intervals that approximate the true value and finally the cumulative probability of completion of the modular bridge construction project is derived. Example experiments were designed using a bridge project at a site in Village A to verify the reasonableness and operability of this paper's combinatorial design theory applied to modular bridge construction schedule optimization.

II. Optimization of bridge construction schedule based on combination design theory

II. A. Theory of the traditional earned value method and related indicators

II. A. 1) Fundamentals of the earned value approach

The Earned Value Method (EVM) [17] can dynamically monitor the overall project cost and progress, and establish a set of evaluation criteria to understand the progress and cost expenditure of the project by formulating a detailed plan in advance, comparing the deviation formed by the budgeted cost and the actual completed cost. In essence, it is deviation analysis, which comprehensively analyzes the progress and cost expenditure of the overall project by introducing intermediate variables.

$$\text{Budgeted cost of Planned work (BCWS)= planned work} \tag{1}$$

II. A. 2) Indicator system for the Earned Value Approach

(1) Basic parameters of the earned value method

1)The budgeted cost of planned work (BCWS), which refers to the total budgeted cost obtained by multiplying the budgeted unit price of the project by the amount of workload at a certain stage according to the pre-established work and schedule plan, is calculated by the formula:

2) The budgeted cost of work performed (BCWP), which is the earned value variable used in the earned value method, refers to the expected total cost of the workload invested in a given phase, obtained by using the amount of work that has already been performed, multiplied by the budgeted unit price of the project, which is calculated by the formula:

$$\text{Budgeted cost of work Done (BCWP)= Work done} \times \text{budgeted unit price} \tag{2}$$

3) the actual cost of completed work (ACWP), refers to a stage of the project has been completed work actually invested in the funds, the use of the progress of work and unit price are for the project carried out to a point in time the actual data, the formula for its calculation:

$$\text{Actual cost of work done (ACWP)= Work done} \times \text{actual unit price} \tag{3}$$

(2) Evaluation indexes of earned value method

1) Cost deviation (CV), which is mainly an objective reflection of the difference between the budgeted cost of completed work (BCWP), and the actual cost of completed work (ACWP), and is calculated by the formula:

$$CV = BCWP - ACWP \tag{4}$$

If CV is greater than 0, it indicates that the budgeted costs are more than the actual costs, the funds are being used relatively efficiently and there is a cost balance;

If CV is equal to 0, it indicates that the budgeted cost is in line with the actual cost, and the project is being implemented in strict accordance with the project plan;

If CV is less than 0, it indicates that the budgeted cost is lower than the actual cost, the efficiency of fund utilization is relatively low, and the cost is overspent.

2) Progress deviation (SV), mainly on the completed work of the budgeted cost (BCWP), the planned work of the budgeted cost (BCWS) of the discrepancy between the objective reflection, its calculation formula is:

$$SV = BCWP - BCWS \tag{5}$$

If SV is greater than 0, it indicates that the completed workload is greater than the planned workload and that the project is progressing at a faster rate;

If SV is equal to 0, it indicates that the completed workload is equal to the planned workload and the project is proceeding according to the planned schedule;

If SV is less than 0, it indicates that the completed workload is smaller than the planned workload and the progress of the project is delayed.

3) Cost Performance Indicator (CPI), which is obtained by the ratio between the budgeted cost of the completed work (BCWP) and the actual cost of the completed work (ACWP), is calculated by the formula:

$$CPI = BCWP / ACWP \tag{6}$$

If the CPI is greater than 1, it indicates that the actual cost of the work performed was lower than the budgeted cost, resulting in a cost balance;

If the CPI is equal to 1, it indicates that the actual cost of work performed was in line with the budgeted cost;

If CPI is less than 1, it indicates that the actual cost of the completed work is higher than the budgeted cost, cost overrun.

4) Schedule Performance Indicator (SPI), obtained by the ratio between the budgeted cost of completed work (BCWP) and the budgeted cost of planned work (BCWS). Its calculation formula is:

$$SPI = BCWP / BCWS \tag{7}$$

If SPI is greater than 1, it indicates that the completed workload is greater than the planned workload and that the project is progressing at a faster rate;

If SPI is equal to 1, it indicates that the completed workload is in line with the planned workload and the progress of the project is in line with expectations;

If SPI is less than 1, it indicates that the completed workload is smaller than the planned workload and the progress of the project is behind.

Earned value method is a scientific method to analyze the cost control situation, which can quantitatively evaluate the performance of the project. By comparing and analyzing the budgeted cost of planned work, the actual cost of completed work and the budgeted cost of completed work of an engineering project, it quantifies the value of cost deviation, so as to make a better assessment of the actual performance of the project.

As can be seen from the index system of the Earned Value Method, the Earned Value Method can control the cost and schedule of the project at the same time. By calculating the cost deviation and schedule deviation, it enables managers to understand the actual cost status of project operation and the actual schedule, which provides a basis for project managers to control the cost of the project as a whole.

Earned value method can predict the cost and time needed to complete the project during the construction process, help project managers understand the overall operation of the project, find out the problems in the project in time and formulate measures to solve them, so as to make the project consistent with the original plan and improve the overall management level of the enterprise.

However, the traditional Earned Value Method is to analyze the cost and schedule from the perspective of the project as a whole, weakening the intrinsic connection between the various work units in the overall project, without considering the possible offsetting of positive and negative deviations for multiple sub-projects, which can lead to a large error in the analysis results when the ignored deviations of sub-projects accumulate into a large number. Since the offset masks the deviations that need to be corrected, it is not possible to control costs in a targeted manner.

The traditional earned value method does not take into account the impact of project quality on construction costs, and it is impossible to determine whether the actual level of project quality meets the expected standards. In the construction process, if the schedule lags due to the actual quality level exceeding the contractually agreed planned quality level, in order to reduce the risk of breach of contract, it will be necessary to invest more costs to catch up with the schedule, or to reduce the quality standard of the subsequent construction to follow the schedule requirements. If the project construction cost exceeds the budget, it is necessary to check whether part of the construction quality exceeds the standard, or whether there is room for cost savings. The traditional earned value method does not realize the integrated management of the three objectives of cost, schedule and quality, and lacks in comprehensive control.

Therefore, this paper proposes the establishment method of new indicators and the critical path earned value method.

II. B. ***Establishment of new indicators and critical path earned value methodology***

II. B. 1) Establishment of key ratios for new parameters

Project implementation process there will be a number of key lines, and because of a variety of factors will lead to changes in the key routes, so the need for a comprehensive analysis of the key routes and non-critical routes, and key work on the key routes may be due to the consumption of different resources and the impact of different routes, which according to the key routes on the different impacts on the progress of each key work on the introduction of a new parameter Critical Ratio (CR), the introduction of the The introduction of CR makes the results more accurate when analyzing the earned value of the project and more targeted when correcting the project.

According to the characteristics of the project in actual construction, the critical ratio of critical work is defined as the ratio of the duration of critical work to the longest duration of the critical path, and the formula is expressed as follows.

$$CR_i = t_i / t_{\max} \tag{8}$$

t_i refers to the duration of the critical job i; $t_{\max}$ refers to the maximum value of the job's duration in the critical path where job i is located; CR_i refers to the critical ratio of job i.

II. B. 2) Critical Path Earned Value Approach

For the traditional earned value method to analyze the characteristics of the overall performance level of the project, and in order to more accurately obtain the performance of the project to obtain the situation, it is proposed that the need to distinguish between the critical path and the non-critical path of the idea, and at the same time, according to the network planning diagram to obtain the critical path of the project, the critical path earned value method is proposed [18]. On the basis of the traditional earned value method, three new basic indexes are introduced, i.e., the budgeted cost of completed work on the critical path $BCWP_{cp}$, the budgeted cost of planned work on the critical path $BCWS_{cp}$, and the actual cost of completed work on the critical path $ACWP_{cp}$. Then there are:

$$SPI_{cp} = BCWP_{cp} / BCWS_{cp} \tag{9}$$

$$CPI_{cp} = BCWP_{cp} / ACWP_{cp} \tag{10}$$

SPI_{cp} refers to the progress performance index on the critical line. If $SPI_{cp} > 1$, it means that the work on the critical line is ahead of schedule; if $SPI_p < 1$, it means that the work on the critical line is behind schedule.

CPI_{cp} refers to the cost performance index on the critical line. If $CPI_{cp} > 1$, it means that the cost of work on the critical line is in balance; if $CPI_{cp} < 1$, it means that the cost of work on the critical line is overspent.

The control of the schedule is a crucial point for the rational monitoring of the project.

II. C. Monte Carlo simulation methods

II. C. 1) Overview of Monte Carlo simulation methods

Monte Carlo simulation method [19], also called stochastic simulation method, is a statistical test method based on probability theory and mathematical statistics. It simulates various situations that may occur in real life through a random number generator, so as to approximate the solution of practical problems. For example, in enterprise value assessment, we can not determine the specific situation of future earnings, but if we can know which variables will have a significant impact on future earnings, and these variables are subject to a certain distribution, then the random number generator can be used to generate random data with the same probability distribution as each random variable, so as to assign values to these variables. Each simulation experiment corresponds to a possible actual situation, repeated n times will get n possible situations, all the above situations will be statistically analyzed to get a range of intervals close to the real value. Therefore, the application of Monte Carlo simulation method must meet two major premises: ① the mathematical model of the target variable is known; ② the probability distribution of each variable in the model is known.

II. C. 2) Monte Carlo simulation fundamentals

The Monte Carlo simulation method is based on probability theory and mathematical statistics, and according to the large number theorem and the central limit theorem, the results of its calculations are convergent and asymptotically obey the normal distribution. In the use of the method, the main concern is the convergence of the random variables and the error.

1) Convergence

Convergence studies of Monte Carlo simulation methods can be inverted to obtain intervals of values of random variables. According to the knowledge of probability theory, Monte Carlo methods are often used to determine the random variable x_1, x_2 by solving for the subsamples $x_1, x_2 \dots x_N$ to determine the approximate value of the random variable X_i by solving for the arithmetic mean of the subsamples $x_1, x_2 \dots$, i.e., $\hat{X} = \frac{1}{N}\sum_{n=1}^{N} x_i = \overline{X}$.

By the Large Numbers Theorem, a sequence of independent identically distributed random variables with finite mathematical expectation $\{X_i\}(i = 1, 2 \dots N)$ has $\lim_{N\to\infty} P\left\{ X_N - \overline{X} | < \varepsilon \right\} = 1$ for any $\varepsilon > 0$, and under the strengthened large number theorem it has $P\{\lim_{N\to x} X_N = \overline{X}\} = 1$, i.e., X_N converges to $\overline{X}$ according to probability $p = 1$ when $N \to \infty$.

From the central limit theorem, if the finite variance of X_i is $\sigma \neq 0$, the random variable $Y_n = (X_i - \bar{X})\frac{\sqrt{N}}{\sigma}$ asymptotically obeys the standard normal distribution when $N \to \infty$, that is, $P\{Y_N < x_\alpha\} \to \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x_\alpha} e^{-\frac{x^2}{2}}dx$. Thus:

$$\begin{aligned} P\{Y_N | < x_\alpha\} &= P\{Y_N < x_\alpha\} - P\{Y_N < -x_\alpha\} \\ &= P\left\{| X_i - \bar{X} | < \frac{X_\alpha \sigma}{\sqrt{N}}\right\} \\ &\approx \frac{2}{\sqrt{2\pi}}\int_0^{x_\alpha} e^{-\frac{x^2}{2}}dx \\ &= 1-\alpha \end{aligned} \tag{11}$$

From the above equation, $| X_i - \bar{X} | < \frac{x_\alpha \sigma}{\sqrt{N}}$ is approximated to be established with probability $1-\alpha$, where α denotes the confidence level, and $1-\alpha$ denotes the confidence interval. In other words, when the confidence level α is determined, the range of values of the random variable can be deduced, i.e., $\left[\bar{X} - \frac{x_\alpha \sigma}{\sqrt{N}}, \bar{X} + \frac{x_\alpha \sigma}{\sqrt{N}}\right]$.

2) Error Estimation

If $\sigma \neq 0$, the error of the Monte Carlo simulation method is $\varepsilon = \frac{x}{a}\sigma\sqrt{N}$, and the error estimate $| X_i - \bar{X} | < \varepsilon = \frac{x_a \sigma}{sqrtN}$, from which we can know that after the confidence level α is determined, the corresponding x_α is known, and the error of the random variable is then determined solely by the standard deviation σ and the number of simulations N. In other words, if the random variable gives more accurate results, it can be achieved by increasing the number of simulations or decreasing the standard deviation of the random variable.

II. C. 3) Common probability distributions in Monte Carlo simulations

This subsection describes the probability distributions used in this paper as follows:

(1) Normal distribution

By definition, if the probability density function of X is:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma}e^{-\frac{(x-\mu)^2}{2\sigma^2}}, -\infty < x < +\infty \tag{12}$$

where μ and $\sigma(\sigma > 0)$ are constants, X is said to obey a normal distribution with mean μ and variance σ, denoted $X \sim N(\mu,\sigma)$.

Its distribution function is $F(x) = P(X \leq x) = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{x} e^{\frac{(t-\mu)^2}{2\sigma^2}}dt$.

The normal distribution is a distribution centered on the mean and symmetrical on both left and right sides, and only the mean and standard deviation are needed for simulation. When the market information is sufficient, the variance decreases, the distribution becomes narrower, and a large amount of data are clustered around the mean, at which time the accuracy of the assessment results is higher.

(2) Uniform distribution

According to the definition, the probability density function of X is:

$$f(x) = \begin{cases} \frac{1}{b-a}, a < x < b \\ 0, else \end{cases} \tag{13}$$

The distribution function is:

$$F(x)=\begin{cases}0, x<a\\ \frac{x-a}{b-a}, a\le x\le b\\ 1, x\ge b\end{cases} \tag{14}$$

The mean is $\frac{a+b}{2}$ and the variance is $\frac{(a+b)^2}{12}$, denoted $XU(a,b)$.

The uniform distribution, also called the rectangular distribution in probability theory and statistics, is defined by the parameters a and b defining the maximum and minimum values on the numerical axis, respectively, and is denoted as $U(a,b)$. A distributional assumption for random variables generally when data information is not readily available or when the cost of obtaining it is large and unimportant.

III. Bridge project implementation of the critical path earned value method implementation effect

This paper selects a bridge project somewhere in village A as the research object, the village is located in the southwestern edge of the Yunnan-Guizhou Plateau, the southeast section of the longitudinal valley of the Hengduan Mountain System, the terrain is inclined from northwestern to southeastern, with an average elevation of 1,400 m. The project area is divided into four distinct seasons, with a dry winter, a hot rainy summer, and an average annual temperature of 12.5 ℃.

Project Construction Scale and Total Cost Estimate The bridge is a continuous girder bridge with a total length of 130m and 6 spans, all of which are concrete prestressed T-beams. The total cost estimate of the bridge is about 25 million RMB. The project is scheduled to start in April 2023 and finish in March 2024.

III. A. Preparation of a work breakdown chart

Project work breakdown structure chart is the construction project in the various tasks according to their relationship with each other for layer by layer decomposition, decomposition into a number of relatively independent, single-content work unit until. Bridge WBS work breakdown structure diagram shown in Figure 1.

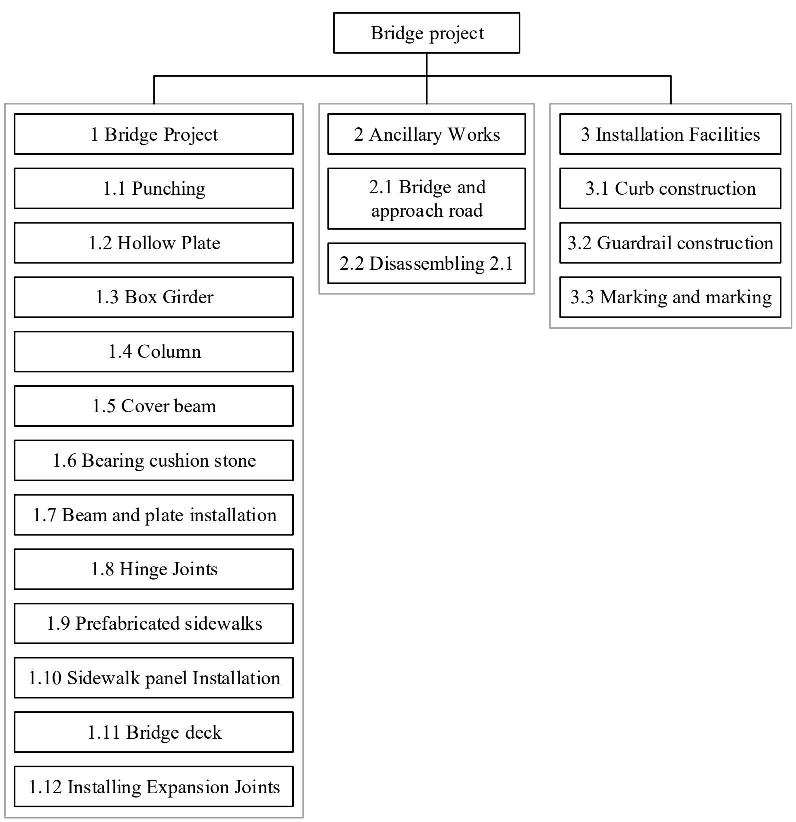

Figure 1: Bridge WBS work breakdown structure diagram

III. B. Calculating the Critical Path for Bridge Projects

Based on Figure 1 and the actual construction sequence of the project, the specific dates of the start to finish of each job, and the calculation of the duration of each job required for completion under normal conditions, a table of the work relationships for the bridge project was drawn. The bridge project work relationships are shown in Table 1.

Table 1: Bridge project work relationship

Job code	Job name	Tight work
A	Bridge and channel	/
B	Precast beam field	/
C	Bridge foundation (punch pile, column, beam)	A
D	Hollow plate prefabrication	B
E	Box girder prefabrication	B
F	Support stone	C
G	Beam mounting	D, E, F
H	reaming	G
I	Bridge dress	H
J	Expansion joint installation	I, K
K	Fence construction	H
L	Sideway board installation	I, K
M	Marking line	J, L
N	Bridge and lead removal	M

Based on the logical relationship between the work, the calculation of the time for each activity of the bridge is shown in Table 2.

Table 2: Activity time calculation results

Job code	Earliest starting time	Earliest end	Late start time	The end of the day	Total jet lag	Free time	Critical path
A	0	40	0	40	0	0	√
B	0	40	45	85	45	45	×
C	40	210	40	210	0	0	√
D	40	170	80	214	40	40	×
E	40	172	80	214	40	40	×
F	210	224	210	224	0	0	√
G	220	252	220	252	0	0	√
H	250	267	250	267	0	0	√
I	260	296	260	296	0	0	√
J	295	305	301	310	6	6	×
K	265	286	273	296	8	8	×
L	295	310	295	310	0	0	√
M	310	315	310	315	0	0	√
N	320	345	320	345	0	0	√

According to the principle of drawing network plan diagram, the network plan of the bridge project is shown in Figure 2. Its key routes are 1→2→3→7→8→9→10→12→13→14→15.

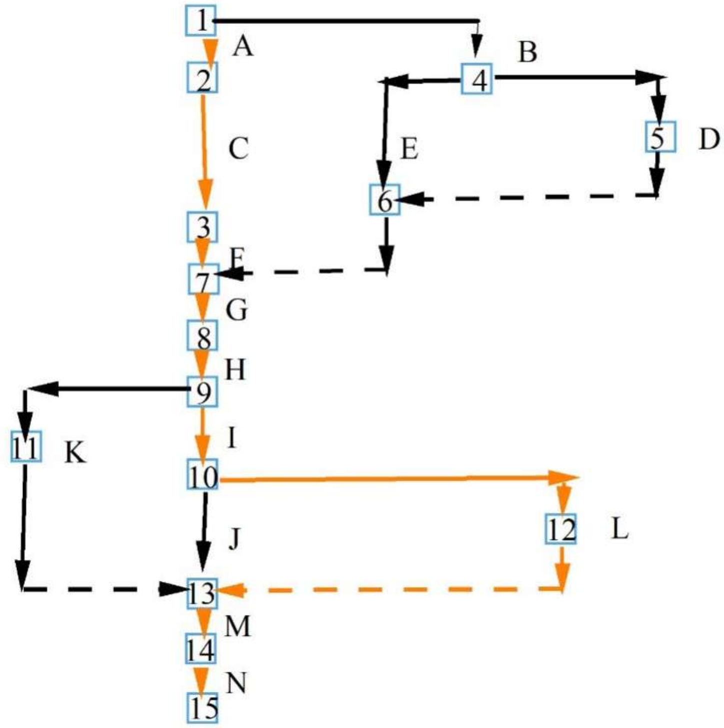

Figure 2: Project network project of bridge project

III. C. Preparation of the bridge project budget

This paper controls the direct costs of the bridge. The direct cost includes labor cost, material cost, machinery use cost and subcontract cost. According to the rolling statistics, the overall budgeted cost of the bridge is shown in Table 3, in which the budgeted cost of Project E is the highest, which reaches 8,955,539 yuan.

Table 3: The overall budget cost of the bridge(yuan)

Project	Labor cost	Materials cost	Mechanical charge	Subcontract charge	Total
A	610058	527415	765412	1452595	3355480
B	265551	300000	200000	350000	1115551
C	939542	2547812	695421	0	4182775
D	409156	394512	113254	1335599	2252521
E	3024556	3172184	213545	2545254	8955539
F	41558	93542	10546	0	145646
G	443554	1654823	815645	0	2914022
H	157555	51845	110254	0	319654
I	215645	809542	50000	0	1075187
J	92354	157451	69540	0	319345
K	310254	293456	127450	524125	1255285
L	92546	57456	60000	0	210002
M	175644	374156	165400	0	715200
N	105213	0	119785	0	224998

III. D. Calculating Earned Value Parameters for the Bridge Project

Based on the earned value reports from April 2023 to May 2023, the data is analyzed. The earned value reports for April and May are now organized to get their cumulative earned value, and the partial and cumulative earned value reports for April to May are shown in Table 4.

The bridge has cost deviation in April and May. The main reason for this is because of material, equipment and subcontract cost overruns. These cost increases were due to higher material prices in the actual project compared to the quota, lower material utilization in the construction site and serious waste during construction, as well as the fact that some workers were not qualified to operate, which made the machines under-utilized, the routine maintenance of the machines was not in place, and there was a shortage of labor due to the lack of proper management of the outsourced labor team and the employees' taking time off from work.

Table 4: Local and cumulative earnings reports(yuan)

Name	Month	
	4	5
Local BCWS(1)	2311545	4275854
Cumulative BCWS(2)	2311545	6593451
Local BCWP (3)	2306548	4277546
Cumulative BCWP (4)	2306548	6589954
Local ACWP (5)	2385451	4384569
Accumulated ACWP(6)	2385451	6799545
Local SV	-4997	1692
Cumulative SV	-4997	-3497
Local CV	-78327	-107023
The cumulative CV	-78327	-209591

IV. Schedule optimization and Monte Carlo simulation

IV. A. Monte Carlo-based single schedule optimization approach

Single schedule optimization based on Monte Carlo simulation methodology used in this project refers to the method of compressing activities with high sensitivity coefficients in order to achieve an empirical value of the cumulative probability of completion without changing the logical relationships of the activities in the project network plan. The optimization is based on the histogram of the cumulative probability of completion and the distribution of sensitivity coefficients obtained at normal completion.

The specific steps are:

1. If the cumulative probability of completion does not reach 90%, identify the activities with the highest sensitivity coefficients for its selection, and adjust the resource plan by the relevant departments to increase its resources and shorten its duration.

2. Enter the data into the computer for Monte Carlo simulation analysis to get the optimized and adjusted cumulative probability of completion and sensitivity analysis data.

3. Repeat steps 1 and 2 until the cumulative probability of completion reaches an acceptable empirical value of 90%.

4. Use the above optimization steps to optimize the project schedule.

Identify the activity with the largest sensitivity coefficient and shorten its duration, i.e., adjust the duration of the activity (construction and installation of steel structures in the plant area) to β-PERT (14, 16, 20) to obtain the histogram of the cumulative probability of completion and the distribution of sensitivity coefficients as shown in Fig. 3 and Table 5, respectively.

The steel structure construction and installation in the installation area is often an important link on the critical path, and shortening its installation time can effectively reduce the delay on the critical path to optimize the construction time of the whole bridge construction project.

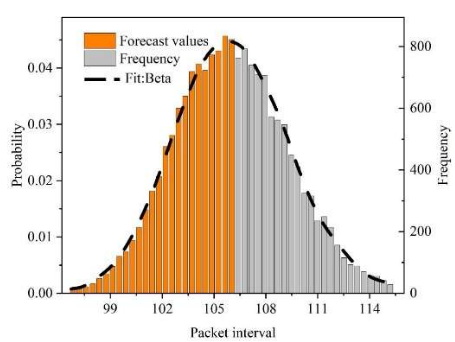

Figure 3: Completion cumulative probability histogram

Table 5: Sensitivity coefficient distribution

Project	Sensitivity coefficient/%
Reactor installation	15.2
Reheat installation	14.4
Antiseptic construction	11.8
Construction of steel structure in unit area	11.0
Condenser installation	10.7
Blow and test	9.2
The third level reaction unit	7.4
Insulation construction	7.2
The secondary reaction unit	6.9
The first order reaction unit pipeline jianan	6.1
Other	0.1

Adjusting the work package (reactor installation) so that its duration is shortened to β-PERT (9, 11, 15), the histogram of the cumulative probability of completion and the distribution of sensitivity coefficients are obtained as shown in Fig. 4 and Table 6, respectively.

The reactor installation may directly affect the subsequent construction process, and the rapid installation of the reactor can ensure the punctuality of the subsequent works and reduce the subsequent effects caused by the delay of this work.

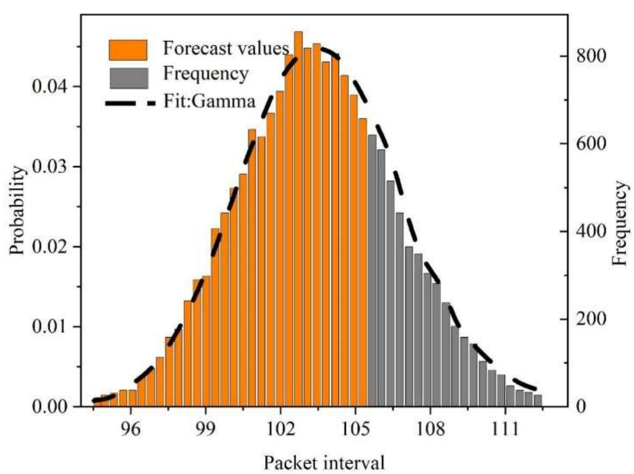

Figure 4: Completion cumulative probability histogram

Table 6: Sensitivity coefficient distribution

Project	Sensitivity coefficient/%
Reactor installation	14.8
Reheat installation	11.8
Antiseptic construction	11.8
Construction of steel structure in unit area	11.5
Condenser installation	10.5
Blow and test	9.6
The third level reaction unit	8.6
Insulation construction	7.5
The secondary reaction unit	7.3
The first order reaction unit pipeline jianan	6.6
Other	0.0

The duration of the activity (reheat furnace installation) is shortened to β-PERT (9, 11, 15), and the histogram of cumulative probability of completion and the distribution of sensitivity coefficients are obtained as shown in Fig. 5 and Table 7, respectively.

The reheating furnace is usually used for steel processing in bridge construction, and shortening the duration of this project can reduce the idle time of the equipment at the construction site and improve the efficiency of equipment use.

Through the scientific and reasonable bridge construction schedule optimization, the construction cycle of steel structure construction and installation, reactor installation and reheating furnace installation in the plant area can be effectively shortened, so that the bridge construction project can be delivered earlier, thus giving full play to its economic and social benefits faster.

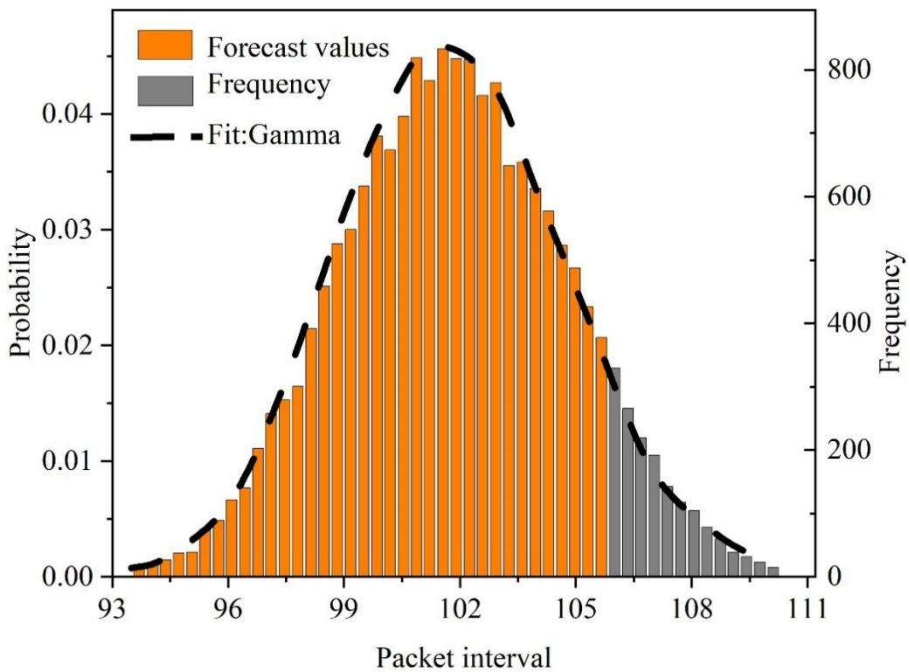

Figure 5: Completion cumulative probability histogram

Table 7: Sensitivity coefficient distribution

Project	Sensitivity coefficient/%
Reactor installation	12.5
Reheat installation	12.5
Antiseptic construction	12.5
Construction of steel structure in unit area	12.3
Condenser installation	10.2
Blow and test	9.7
The third level reaction unit	9.0
Insulation construction	7.9
The secondary reaction unit	6.9
The first order reaction unit pipeline jianan	6.3
Other	0.2

IV. B. Monte Carlo-based cost-schedule optimization

According to the previous description, when using the Monte Carlo simulation-based cost-schedule method to optimize and adjust the schedule, in addition to meeting the Monte Carlo simulation optimization principles mentioned above, it is also necessary to consider the principle of cost minimization, i.e., it is hoped that through the optimization and adjustment, not only to meet the cumulative probability of completion to reach the empirical value, but also hope to minimize the corresponding costs of the plan at the same time. Resource-schedule optimization method is more suitable for dynamic schedule adjustment in the process of project implementation, which can reasonably determine the number of various temporary facilities on the bridge construction site to ensure that the allocation of bridge construction resources is more reasonable, so as to achieve not only to ensure the bridge construction schedule, but also to achieve the purpose of saving resources.

Reducing the direct cost of all C activities makes them last longer, and the cumulative probability of completion histogram and the distribution of sensitivity coefficients obtained through Monte Carlo simulation are shown in Fig. 6 and Table 8, respectively.

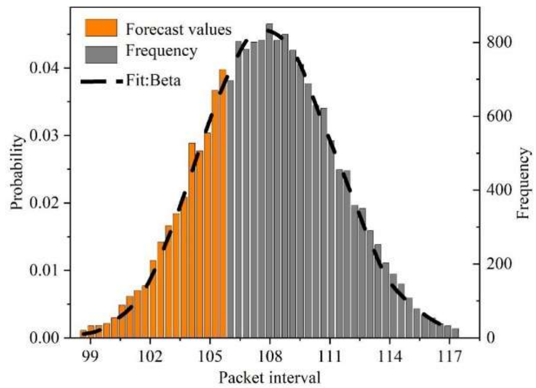

Figure 6: Completion cumulative probability histogram

Table 8: Sensitivity coefficient distribution

Project	Sensitivity coefficient/%
Reactor installation	19.5
Reheat installation	14.7
Antiseptic construction	13.2
Construction of steel structure in unit area	11.4
Condenser installation	11.4
Blow and test	7.2
The third level reaction unit	7.0
Insulation construction	6.9
The secondary reaction unit	5.8
The first order reaction unit pipeline jianan	2.8
Other	0.1

Increasing the direct cost of the activity (reheat furnace installation) so that its duration is shortened to β-PERT (9, 11, 15) yields a histogram of the cumulative probability of completion and a distribution of sensitivity coefficients as shown in Fig. 7 and Table 9, respectively.

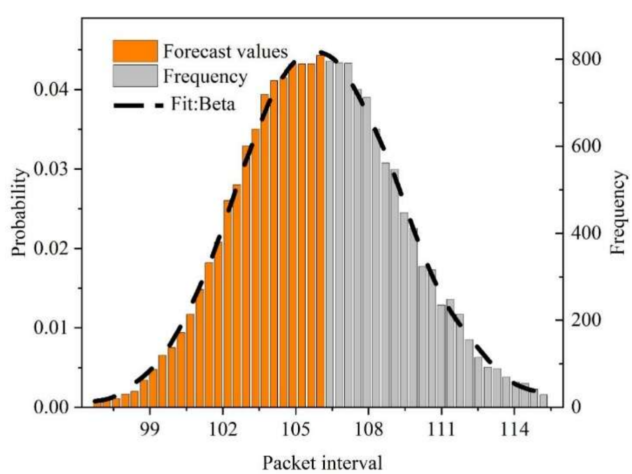

Figure 7: Completion cumulative probability histogram

Table 9: Sensitivity coefficient distribution

Project	Sensitivity coefficient/%
Reactor installation	21.5
Reheat installation	14.5
Antiseptic construction	11.6
Construction of steel structure in unit area	11.4
Condenser installation	10.9
Blow and test	7.2
The third level reaction unit	7.1
Insulation construction	6.9
The secondary reaction unit	6.3
The first order reaction unit pipeline jianan	2.5
Other	0.1

From Fig. 7, it can be seen that the cumulative probability of completion has not reached the empirical value of 90%, so it is necessary to continue the optimization by applying the same method to increase the direct cost of the activity (reactor installation) to shorten its duration to β-PERT (9, 11, 15), and obtain the histogram of the cumulative probability of completion and the distribution of sensitivity coefficients as shown in Fig. 8 and Table 10, respectively.

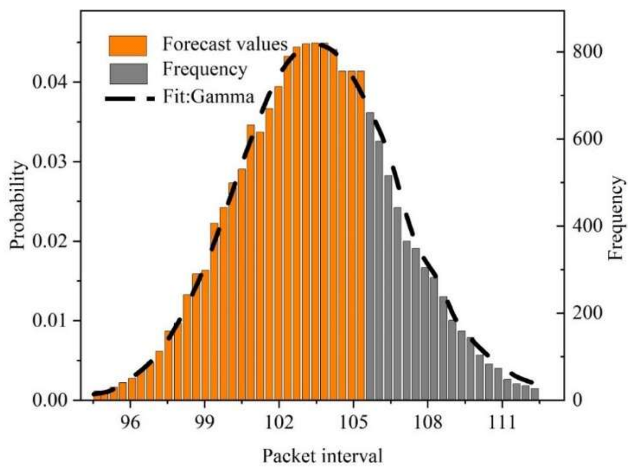

Figure 8: Completion cumulative probability histogram

Table 10: Sensitivity coefficient distribution

Project	Sensitivity coefficient/%
Reactor installation	20.3
Reheat installation	12.7
Antiseptic construction	12.4
Construction of steel structure in unit area	11.7
Condenser installation	11.3
Blow and test	8.5
The third level reaction unit	7.2
Insulation construction	6.9
The secondary reaction unit	6.2
The first order reaction unit pipeline jianan	2.7
Other	0.1

Similarly, increase the direct cost of the activity (anticorrosion construction), so that its duration is shortened to β (11, 12, 16), to obtain the histogram of the cumulative probability of completion and the distribution of sensitivity coefficients as shown in Fig. 9 and Table 11, respectively, at this time, the cumulative probability of completion reaches 90.458%, and it is considered that the schedule has a high degree of reliability, and it is able to be accepted by the project managers or decision makers.

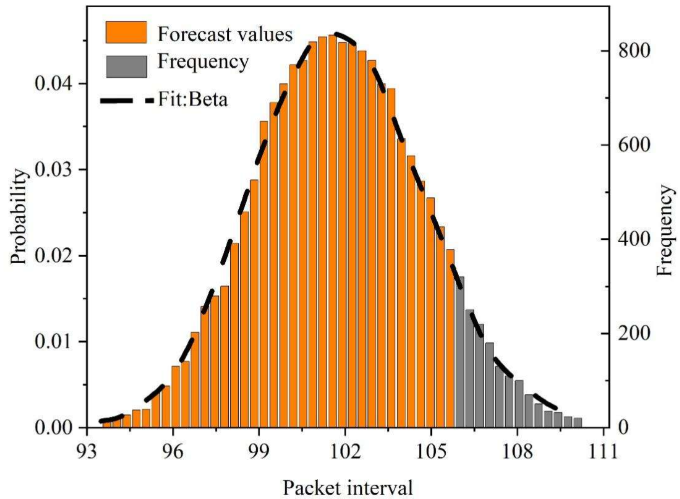

Figure 9: Completion cumulative probability histogram

Table 11: Sensitivity coefficient distribution

Project	Sensitivity coefficient/%
Reactor installation	19.5
Reheat installation	14.7
Antiseptic construction	13.2
Construction of steel structure in unit area	11.4
Condenser installation	11.4
Blow and test	7.2
The third level reaction unit	7.0
Insulation construction	6.9
The secondary reaction unit	5.8
The first order reaction unit pipeline jianan	2.8
Other	0.1

V. Conclusion

In this study, the critical path earned value method is combined with Monte Carlo simulation method and applied to modular bridge construction schedule optimization, and certain research results are obtained.

The results show that the critical path Earned Value Method can be used to explore the critical path of a bridge construction project, identify the main modules of schedule control for a modular bridge construction project, and focus on the schedule and cost deviation of the activities on the critical path of a modular bridge construction project. The main reasons for the cost deviation in April and May, i.e., the existence of serious overruns in material, equipment and subcontracting costs, are deeply excavated to provide strong support for project managers to formulate reasonable schedule optimization strategies.

Both the Monte Carlo-based single schedule optimization method and the cost-schedule optimization method mentioned in the paper can make the cumulative probability of completion reach the empirical value of 90%. The cost-schedule optimization is more suitable for the optimization and adjustment of the schedule plan in the bidding stage. After a series of project time reduction, the completion cumulative probability of the modular bridge construction project in this paper reaches 90.458%. The Monte Carlo-based cost-schedule optimization method not only needs to pay attention to whether the schedule can meet the requirements of the bid, but also focuses on the total cost of the whole project, which is closely related to the economic benefits of the enterprise. The cost-schedule optimization method is more in line with the needs of project schedule optimization. The experimental results show that the method of this paper effectively improves the schedule control efficiency of modular bridge construction projects, and can provide more reliable scheduling plans for the implementation of specific projects.

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