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PROJECT BUFFER SETTING AND DYNAMIC MONITORING OF A CRITICAL CHAIN ON CONSIDERATION OF MULTIPLE RISK FACTORS

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Aiming at the deficiency of buffer setting and monitoring, this paper proposes a buffer calculation method considering the influence of uncertainty factors and establishes a buffer dynamic monitoring model. In this method, fuzzy analytic hierarchy process (FAHP) is used to assign weights to the uncertainty impact factors, set the buffer monitoring index, and then dynamically monitor the actual situation of the project through real-time monitoring threshold. After the deviation of the monitoring threshold value of a monitoring point occurs, the impact rate of the delay at the execution time of the process is further calculated to determine whether it is necessary to take steps to correct the deviation. Finally, the rationality of this paper is verified by the case analysis and Monte-Carlo Simulation.

Keywords: Uncertainty Factor, Dynamic Monitoring, Critical Chain, Simulation

1. Introduction

The engineering project is a complex activity involving many aspects, which characterized as being large-scale, high investment, long duration and many participants. However, different kinds of risk factors occur in different stages of the project, and these factors may influence the schedule, thereby causing duration delay or substantial losses. Therefore, managing the schedule effectively has been an essential part of project management.

With the rapid development of construction economy, the scale of engineering projects is becoming larger, the complexity of construction process is

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increasing, and more and more uncertain risk factors faced by the project are emerging, so the project scheduling is becoming more difficult. Goldratt [1] introduced the theory of constraints (TOC) in project management, and put forward the theory of critical chain project management (CCPM) after CPM and PERT. Rand [2] believes that the traditional milestone thinking tends to cause project delay. Steyn [3,4] believes that the critical chain is another significant milestone in the development of project management after PERT and CPM. Leach [5] believes that CCPM is superior to traditional project management theory in many aspects. In order to protect the critical chain, Goldratt introduces the concept of buffer which can be calculated to reflect the uncertainty in the estimates of duration of tasks [6]. Radovilsky [7] proposes that the buffer size could be calculated by using the M/M/1/K model based on queuing theory. Hod [8], Luong Due Long [9], Xu et al [10]. Suggest using Monte-Carlo, fuzzy critical chain, Bayes method to estimate the buffer size. Ma et al. [11], Hu et al. [12] and Jiang et al. [13] put forward a buffer calculation approach considering the uncertainty of activity duration, the information and the resource impact. Zhang et al. [14] establish an effort buffer monitoring and control model to monitor and control software project effort in an effective manner. Hu et al. [15] develops a new two-stage buffer monitoring approach based on a statistical process control.

In summary, buffer setting and monitoring are two important issues of project critical chain buffer management. The accurate buffer setting and reasonable buffer monitoring can effectively improve the completion rate, shorten the duration and reduce the cost of the project. However, most of these researches above do not fully consider the influence on buffer setting and monitoring of the uncertainty risk factors in dynamic construction environment. For this reason, we introduce a new method of critical chain buffer setting and dynamic monitoring, which considers four kinds of uncertainty factors during the construction reasonably and is more in accordance with the project's actual situation.

2. Critical chain buffer setting model

2.1 Analysis of Influencing Factors for Buffer Setting

(1) Risk preference coefficient (RPC)

Generally, the project managers need to estimate the activities' duration according to the risk environment of the project which shows the project managers' risk preference. The project managers need approximately estimate the optimistic time (*a*), the most likely time (*m*) and the pessimistic time (*b*) of each activity. We can define the risk preference coefficient (α_i) to reflect the project managers' consideration of risk preference which can be calculated as follows:

$$\alpha_i = \frac{m_i - a_i}{b_i - a_i} \tag{1}$$

(2) Complexity degree of network plan (CDNP)

In fact, the schedule network of a large-scale engineering project often contains more activities and more complex logical relations. However, the more complex the network plan, the more difficult it is to control the schedule, so more buffers need to be configured to absorb the schedule risk when setting buffers. We can define the complexity degree (β_i) of network plan as:

$$\beta_i = \frac{N_{pi}}{N_T} \tag{2}$$

where N_{pi} is the number of precedence activities of activity i; N_T is the total number of activities on the chain which contains activity i.

(3) Influence coefficient of activity position (ICAP)

The actual engineering application shows that with the implementation of the project plan, the schedule deviation keeps accumulating, and the risk of schedule delay is increasing. Therefore, when the buffer size is determined, we must consider the influence of activity position to the buffer setting, and use an index to measure it which is called influence coefficient of activity position (χ_i).

$$\chi_i = \frac{T_i}{T_s} \tag{3}$$

where T_i is the duration from the beginning of critical chain to the middle point of activity i; T_s is the total duration from the beginning to the end of the project.

(4) Resources influence coefficient (RIC)

During the actual implementation of large construction projects, there are a great variety of resources with large quantities needed, and each activity will consume different resources. Therefore, it is necessary to consider the influence of resource constraints on the buffer setting of critical chain. Here, we can use an index called resources influence coefficient (RIC) to describe the influence.

We can calculate resources influence coefficient (δ_i) as follows:

$$\delta_i = \sum_k u_{ik} \omega_k \tag{4}$$

where u_{ik} is the resources utilization degree of activity i for resource k; ω_k is the resources constrained degree of resource k.

2.2 Buffer Setting Model Based on FAHP

(1) Buffer Setting on Consideration of Multiple Risk Factors
Step 1. Calculate the expected duration (t_i) of each activity;

$$t_i = \frac{(a_i + 4m_i + b_i)}{6} \tag{5}$$

Step 2. Identify the four risk coefficients RPC(α_i), CDNP(β_i), ICAP(χ_i) and RIC(δ_i) with Eq. (1), (2), (3) and (4);

Step 3. Determine the weight of four risk factors with fuzzy analytic hierarchy process (FAHP);

Step 4. Calculate the safety time (Δt_i) of each activity;

$$\Delta t_i = t_i - a_i \tag{6}$$

Step 5. Buffer setting.

If there are *n* activities before the noncritical chain joins the node of the critical chain, the FB can be calculated as:

$$FB = \sqrt{\sum_{i=1}^{n}\left[\left(1+\eta_1 \cdot \alpha_i + \eta_2 \cdot \beta_i + \eta_3 \cdot \chi_i + \eta_4 \cdot \delta_i\right)\Delta t_i\right]^2} \tag{7}$$

where Δt_i is the safety time of activity i in noncritical chain; $\eta_1, \eta_2, \eta_3, \eta_4$ are the weight of risk factors.

Assuming that there are *m* activities in the critical chain, then PB is:

$$PB = \sqrt{\sum_{i=1}^{m}\left[\left(1+\eta_1 \cdot \alpha_i + \eta_2 \cdot \beta_i + \eta_3 \cdot \chi_i + \eta_4 \cdot \delta_i\right)\Delta t_i\right]^2} \tag{8}$$

where Δt_i is the safety time of activity i in critical chain; $\eta_1, \eta_2, \eta_3, \eta_4$ are the weight of risk factors.

Assuming that there are H_1 critical chains and H_2 noncritical chains in the network plan of an actual project. The project activity is represented by *i*. Then the buffer allocation quantity B_i^H of each activity is:

$$B_i^{H_1} = PB^{H_1} \times \left(\eta_1 \cdot \frac{\alpha_i}{\sum_{i=1}^{n}\alpha_i} + \eta_2 \cdot \frac{\beta_i}{\sum_{i=1}^{n}\beta_i} + \eta_3 \cdot \frac{\chi_i}{\sum_{i=1}^{n}\chi_i} + \eta_4 \cdot \frac{\delta_i}{\sum_{i=1}^{n}\delta_i} \right) \tag{9}$$

$$B_i^{H_2} = FB^{H_2} \times \left(\eta_1 \frac{\alpha_i}{\sum_{i=1}^{m} \alpha_i} + \eta_2 \frac{\beta_i}{\sum_{i=1}^{m} \beta_i} + \eta_3 \frac{\chi_i}{\sum_{i=1}^{m} \chi_i} + \eta_4 \frac{\delta_i}{\sum_{i=1}^{m} \delta_i} \right) \tag{10}$$

(2) FAHP determines the weight of Multiple Risk Factors

Step 1: To establish the fuzzy consistency judgment matrix *A*. In FAHP [16, 17], the scale method of 0.1-0.9 is used to make mutual comparison of the two factors, so as to obtain the fuzzy consistency judgment matrix $A = \left(a_{ij}\right)_{n \times n}$.

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} \tag{11}$$

Step 2: On the basis of fuzzy complementary judgment matrix, the fuzzy consistent matrix is transformed as follows.

$$b_{ij} = \frac{a_i - a_j}{2n} + 0.5 \tag{12}$$

where a_i and a_j are the sum of the elements of row *i* and column *j* in matrix *A*, b_{ij} is the element value of row *i* and column *j* in the fuzzy consistency matrix.

Step 3: Calculating the weight of 4 risk factors (η_i) according to the fuzzy consistency matrix.

$$\eta_i = \frac{\sum_{j=1}^{n} b_{ij} + \frac{n}{2} - 1}{n\left(n-1\right)}, i = 1, \ldots, 4 \tag{13}$$

Step 4: Consistency test of fuzzy complementary judgment matrix. If *A* passes the consistency test, the weight value is reasonable.

3. Buffer dynamic monitoring model for critical chain

3.1 Determination of buffer monitoring parameters

Taking the example of a project with *H* chains, assume that PD_{it}^{h} is the planned duration of activity *i* on chain *h* at time *t*, AD_{it}^{h} is the actual duration of activity *i*, ρ_{it}^{h} is the completion percentage of the activity *i*, ED_{it}^{h} is the duration of the project that has been executed, RD_{it}^h is the duration of the remainder of the project, and BC_{it}^h is the project buffer consumption [18,19,20]. Then AD_{it}^h, RD_{it}^h and BC_{it}^h can be calculated as follows:

$$AD_{it}^h = ED_{it}^h / \rho_{it}^h \tag{14}$$

$$RD_{it}^h = ED_{it}^h \times \left(1-\rho_{it}^h\right) / \rho_{it}^h \tag{15}$$

$$BC_{it}^h = \sum_{k=1}^{i-1} AD_{kt}^h + ED_{it}^h / \rho_{it}^h - \sum_{k=1}^{i} PD_{kt}^h \tag{16}$$

Dynamic monitoring mainly judges the project status through real-time monitoring threshold (o_i) as follows:

$$o_i = \frac{BR_t^h}{FB^{H_2} - BC_{it}^h} \tag{17}$$

$$o_i = \frac{BR_t^h}{PB^{H_1} - BC_{it}^h} \tag{18}$$

where BR_t^h is the buffer size required for the remaining of chain *h* at time *t*, it can be calculated as:

$$BR_t^h = \left(\eta_1 \cdot \frac{\alpha_i}{\sum_{i=1}^{n} \alpha_i} + \eta_2 \cdot \frac{\beta_i}{\sum_{i=1}^{n} \beta_i} + \eta_3 \cdot \frac{\chi_i}{\sum_{i=1}^{n} \chi_i} + \eta_4 \cdot \frac{\delta_i}{\sum_{i=1}^{n} \delta_i} \right) RD_{it}^h + \sum_{k=i+1}^{n^h} B_i^h \tag{19}$$

3.2 Determination of early warning value

When $o_i > 1$, it means the actual schedule of the project has fallen behind the planned schedule. Therefore, it is significant to select the node to take corrective measures. In this paper, the delay effect rate (υ_t) is used for judgment.

$$\upsilon_t = \frac{BR_t^h + BC_{it}^h - FB^h}{FB^h - BC_{it}^h} \tag{20}$$

(1) When $0 < \upsilon_t < 1/3$, it means the project schedule is normal, the manager needs no measure to take immediately, but they need strengthen monitoring. (2) When $1/3 < \upsilon_t < 2/3$, it means the project schedule is abnormal, the manager should

analyze the reasons for delay, and take corresponding corrective measures in time. (3) When $2/3 < \upsilon_t < 1$, it means the project schedule is extremely abnormal. Therefore, the manager should take corresponding corrective measures immediately.

4. Case Study

The reservoir chosen for this paper is located in the upper reaches of the Jiangli River (a tributary of the Nanhe River in the upper reaches of the Yangtze River) in Chongqing, China. The normal water storage level of the reservoir is 433.50m, the designed flood level is 434.79m and the check flood level is 435.15m.The total capacity of this reservoir, as a daily regulating one, is 1.09 million m^3.

4.1 Buffer setting

The specific activity, logical relationship and resource requirements of a reservoir reinforcement project are shown in Table 1. The maximum supply of mechanical equipment is 20 units.

Table 1

Activity information of the reservoir reinforcement project

The name of the project	Activity ID	Activity name	Predecessor activities	The optimistic time (*a*)/days	The most likely time (*m*)/days	The pessimistic time (*b*)/days	The required resources (The quantity of mechanical equipment)
Spillway reinforcement curtain grouting	A	Preparation for construction	--	5	7	10	0
	B	Foundation cleaning of grouting platform	A	6	10	12	3
	C	R150 concrete pouring	B	14	16	20	4
	D	Drilling grouting holes on dam crest	C	46	50	54	12
	E	Curtain grouting1	D	56	62	64	13
	F	Drilling grouting holes at right bank-abutment	C	38	40	45	8
Right bank spillway inlet dam head reconstruction	G	Earth excavation	A	12	15	19	7
	H	Anchor bar installation	G	10	10	12	6
	I	Pouring concrete protective face	H	15	18	20	9
	J	Pouring concrete retaining wall	I	45	48	52	14
	K	Sand gravel backfilling	J	46	48	52	10
Temporary diversion hole seal	L	Drilling grouting holes	A	12	15	18	5
	M	Curtain grouting2	L	15	16	18	5
	N	access hole	E	8	10	12	4
Spillway reinforcement curtain grouting	O	Curtain grouting3	F、N	46	50	55	8
	P	access hole	O、M	10	12	15	4
	Q	Construction site cleaning	P、K	6	9	12	5

Calculate the activity parameters as shown in Table 2.

Table 2

Activity parameter calculation

Activity ID	t_i /days	Δt_i /days	α_i	β_i	χ_i	δ_i	Activity ID	t_i /days	Δt_i /days	α_i	β_i	χ_i	δ_i
A	7	2	0.40	0	0.01	0.00	J	48	3	0.43	0.14	0.33	0.06
B	10	4	0.67	0.11	0.04	0.04	K	48	2	0.33	0.14	0.56	0.10
C	16	2	0.33	0.11	0.09	0.05	L	15	3	0.50	0.20	0.06	0.06
D	50	4	0.50	0.11	0.24	0.08	M	16	1	0.33	0.20	0.12	0.06
E	61	5	0.75	0.11	0.50	0.05	N	10	2	0.50	0.11	0.64	0.05
F	41	3	0.29	0.14	0.22	0.15	O	50	4	0.44	0.22	0.80	0.10
G	15	3	0.43	0.14	0.06	0.09	P	12	2	0.40	0.22	0.94	0.05
H	10	0	0.00	0.14	0.11	0.08	Q	9	3	0.50	0.22	0.98	0.06
I	18	3	0.60	0.14	0.18	0.06							

The fuzzy judgment matrix of uncertain risk factors given by various experts is as follows:

$$A = \begin{bmatrix} 0.5 & 0.4 & 0.3 & 0.7 \\ 0.6 & 0.5 & 0.5 & 0.6 \\ 0.7 & 0.5 & 0.5 & 0.4 \\ 0.3 & 0.4 & 0.6 & 0.5 \end{bmatrix} \tag{21}$$

The weight-vector of A is $\eta = (0.2458, 0.2583, 0.2542, 0.2417)$.

The final critical chain network diagram is shown in Fig. 1. The buffer allocation of each chain is: $FB^1 = 2.042$, $FB^2 = 2.470$, $FB^3 = 1.696$, $PB = 3.187$.

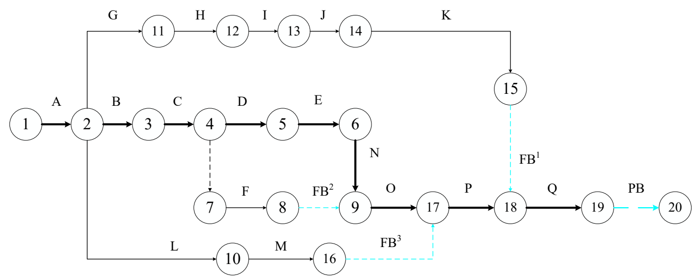


Fig. 1. Schematic diagram of buffer setting

4.2 Dynamic monitoring

Set up monitoring points according to the actual completion of the project to calculate the corresponding monitoring indicators shown in Table 3.

Table 3

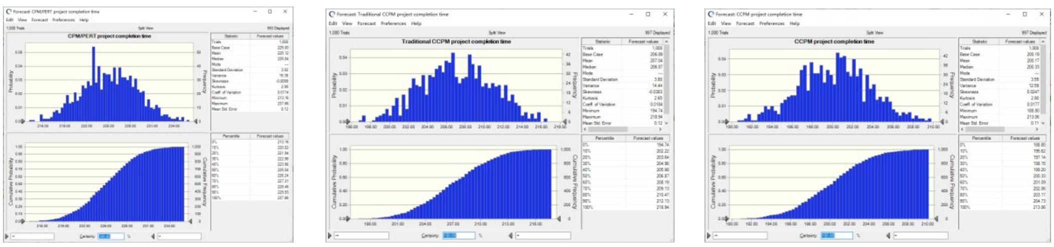
Calculation table of monitoring parameters of monitoring points

Monitoring point	AD_{it}^{h}	ED_{it}^{h}	ρ_{it}^{h}	RD_{it}^{h}	BC_{it}^{h}	BR_{t}^{h}	o_i
1	7	7	100%	0	4	5	0.2632
2	10	10	100%	0	8	6	0.4000
3	16	16	100%	0	12	10	0.9091
4	50	46	92%	4	46	29	0.6170
5	62	56	90%	6	60	35	**1.5217**
6	10	10	100%	0	8	6	0.1091
7	50	46	92%	4	45	37.11	**1.6389**
8	12	12	100%	0	9	7.5	0.5357
9	9	9	100%	0	6	6	0.3529

From Table 3, we can see that the monitoring threshold (o_i) of monitoring point 5 and 7 is bigger than 1. It indicates that the actual schedule of the project may fall behind the planned schedule at the monitoring point 5 and 7. The calculation result shows that υ_5 =36.57% and υ_7 = 37.11% which are both within the range of [1/3, 2/3]. This indicates that the schedule deviation has a tendency of further expansion in the plan execution. In fact, during the curtain grouting, there was a serious water surge in the drilling hole, so the schedule was delayed. The analysis results are consistent with the actual situation of the project.

4.3 Monte Carlo simulation

Firstly, the schedule model based on CPM / PERT, traditional CCPM and improved CCPM is established in Excel, and the logical relationship between each activities (17 activities in all) is defined. Then, the duration of the 17 activities and 4 buffers are set as "Define Assumption" and are subject to the specific distribution (such as triangular distribution, normal distribution, β distribution and so on). Next set the earliest completion time of the project as the "Define Forecast". Finally, the schedule model were run 1000 times and the simulation results are obtained. The simulation results are shown in the Fig. 2 and Table 4.



(a) CPM/PERT (b) Traditional CCPM (c) CCPM

Fig. 2. Simulation results

Table 4

Table of simulation results

	Base Case	Mean	Median	Mode	Standard Deviation	Variance
CPM/PERT	225.00	225.12	225.04		3.92	15.35
Traditional CCPM	206.89	207.04	206.87		3.80	14.44
Improved CCPM	200.19	200.17	200.33		3.55	12.59
	Skewness	Kurtosis	Coeff.of Variation	Minimum	Maximum	Mean Std. Error
CPM/PERT	-0.0099	2.90	0.0174	213.16	237.66	0.12
Traditional CCPM	-0.0383	2.65	0.0184	194.74	218.94	0.12
Improved CCPM	0.0247	2.90	0.0177	188.80	213.06	0.11

According to the simulation results, it can be known that the project duration calculated by CPM/PERT and traditional CCPM is 225 and 207 days, but the duration calculated by improved CCPM (considering the four risk factors) is 200 days after. Therefore, after considering the influence of four risk factors on the project, the allocation of the buffer size (PB and FB) is more reasonable, it can absorb the influence of uncertain factors on the project duration and ensure the normal completion of the project.

Monte Carlo technology was used to simulate the implementation activity of project plan, and the statistical frequency number of delay effect rate was counted in Table 5:

Table 5

Statistical table of simulation results of critical chain dynamic monitoring system

Method	Range	Activity								
		A	B	C	D	E	N	O	P	Q
Traditional buffer monitoring method(TBMM)	$0 < \upsilon_t < 1/3$	999	999	997	997	963	932	910	886	862
	$1/3 < \upsilon_t < 2/3$	1	1	3	3	30	37	52	78	84
	$2/3 < \upsilon_t < 1$	0	0	0	0	7	31	38	36	54
Traditional dynamic buffer monitoring method (TDBMM)	$0 < \upsilon_t < 1/3$	998	998	996	996	978	969	954	923	892
	$1/3 < \upsilon_t < 2/3$	2	2	3	4	21	23	42	64	96
	$2/3 < \upsilon_t < 1$	0	0	1	0	1	8	4	13	12
New dynamic buffer monitoring method(NDBMM)	$0 < \upsilon_t < 1/3$	1000	1000	1000	997	978	966	964	986	992
	$1/3 < \upsilon_t < 2/3$	0	0	0	3	21	33	32	12	8
	$2/3 < \upsilon_t < 1$	0	0	0	0	1	1	4	2	0

From Table 5, the results show that: Firstly, the frequency number falls in the areas of [1/3, 2/3] and [2/3, 1] increases with the progress of the project, while that in the areas of [0, 1/3] decreases significantly. It suggests that the buffer is gradually consumed and progress deviation occurs and the risk of delay increases as the project progresses. At this time, the causes of deviation need to be analyzed and necessary deviation correction measures should be taken. Secondly, at the beginning of the project, the buffer consumption is almost in the [0, 1/3], and a little buffer consumption is in the [1/3, 2/3] and [2/3, 1] in the later stages. This indicates that the problems existing in the early stage of the project are accumulating and the probability of project delay is very high. Finally, comparison with TBMM and TDBMM, the new dynamic buffer monitoring method (NDBMM) proposed by us comprehensively shows only 0.4% buffer consumption is in the [2/3, 1], which proves the effectiveness of monitoring.

5. Conclusions

We analyze the influencing factors for buffer setting and discuss how to deal with these risk factors, and then build a buffer setting model based on uncertain risk factors and FAHP. On the other hand, a dynamic buffer monitoring model is proposed to monitor the real-time status of project's schedule and make a reasonable suggestion for schedule controlling. Finally, the application of the proposed models in a real case of reservoir reinforcement project schedule controlling is elaborated. The result shows that the simulation results with the model proposed by us are is consistent with the actual situation of the project, which can better reflect the project implementation information and guide the project managers to take more appropriate decisions to ensure the completion of the project on time.

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