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Multi-project buffer setting and dynamic monitoring of a critical chain based on comprehensive factors

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ABSTRACT

The paper introduces a new multi-factor critical chain buffer estimation model and designs a dynamic monitoring method based on the project elements. A literature analysis determined a research gap and a research problem. It was found that the existing methods offer scarce collaborative studies on buffer setting and monitoring and insufficient research on buffer setting considering project economic indicators. However, these topics are often given priority consideration in practical engineering applications. Therefore, the study proposes a multi-factor critical chain buffer setting and its dynamic monitoring method. The planning stage analyses the impact of income, resources, and probability of success on buffer size setting and defines the calculation model of capacity constraint buffer. The execution stage dynamically sets buffer monitoring points according to the progress of project implementation, monitors the remaining buffer amount at the completion of each activity on the critical chain, and takes corresponding actions to ensure that the progress is controllable. The method was applied in a multi-project of a Chinese software enterprise. To further verify the effectiveness of this research, the method is compared with the traditional static buffer monitoring method (TBMM) and the relative buffer monitoring method (RBMM), and the construction period of the real project is simulated through the computer program for analysis. Results show that the research method can reduce unreasonable buffer settings, enhance the robustness of a buffer against complex environments, and reduce the probability of false warnings in the monitoring process.

KEY WORDS

multi-project management, critical chain method, buffer setting, dynamic monitoring

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Introduction

The developing economy produces a more competitive environment and greater uncertainty for the software industry. Many software enterprises encounter resource limitations and schedule control issues in multi-project implementation (An et al., 2024; Peng & Peng, 2022). The critical chain, a method developed from the constraint theory, has been regarded as an effective approach to solving these dilemmas (Tukel et al., 2006; Zhao et al., 2024). It focuses on the critical factors limiting the achievement of project objectives,

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considers the relationship between activity constraints and resource constraints from the perspective of global optimisation, and finds the critical chain that determines the overall progress based on the discrimination principle that activities on the path have no room for delaying (Peng & Peng, 2022; Zhang & Han, 2023b). The buffer concept is introduced to reduce the impact of uncertain factors on the progress of project execution. By reducing the safety time and increasing the buffer, the critical chain method can shorten the project planning cycle, use the buffer to absorb the adverse impact of the delay on the overall schedule and improve the probability of completion on time (She et al., 2021; Zhang et al., 2018). A theoretical review of buffer management research shows two main directions, i.e., buffer settings and monitoring (Bredael & Vanhoucke, 2024; Zhang & Han, 2023a). The basic logic of using critical chain methods for multi-project management could also be summarised from previous literature (Zhang & Han, 2023b; Zhao et al., 2024).

The planning stage analyses the capacity constraint resource (CCR) of a multi-project to eliminate the resource conflict of the CCR and use heuristic algorithms (such as genetic algorithms etc.) to identify the system critical chain of the multi-project (Satic et al., 2024). At the same time, to avoid the delay of the drum activity of the former project affecting the start of the latter project, a capacity constraint buffer (CCB) is set for a multi-project system critical chain between the activity that uses the CCR last in the preceding project and the activity that uses the CCR first in the following project (Zhang & Han, 2023a). Here, a multi-project will be regarded as a single project with the critical activity chain as the critical chain (Bu et al., 2021). The execution phase analyses the buffer consumption based on the determined CCB to monitor whether multiple projects are delayed and corresponding measures are taken to ensure the timely completion of the projects (Trietsch, 2005).

Inspired by the literature and the concept of collaborative design (Dalouchei et al., 2022; Ghoddousi et al., 2017; Li et al., 2022; Luong Duc & Ohsato, 2008), this paper comprehensively considers factors such as project importance, resource scarcity, and risk resilience to set buffer size. Furthermore, real-time monitoring of the current active buffer consumption can be achieved by dynamically setting buffer monitoring points. Finally, combining case studies truly reflects the implementation of the proposed method, providing a basis for project schedule management decision-making and helping enterprises reduce the occurrence of erroneous warnings.

1. Literature review

Classic methods of buffer setting include the cut and paste method (C&PM) proposed by Goldratt and the root square error method (RSEM) proposed by Newbold in the 1990s (Bie et al., 2012). Although C&PM is simple to operate, the size of the buffer is directly related to the length of the critical chain. So, it is easy for C&PM to produce a buffer that is too large or too small; therefore, the method is rarely used in practice (Bakry et al., 2016). Contrastively, RSEM is based on the root of the sum of the variance of the safe time of all activities, which avoids arbitrarily reducing or increasing the estimated time of each activity and reduces subjective blindness (Hu et al., 2017).

On this basis, many scholars make improvements according to the project attributes (Goudarzi et al., 2024; Mozhdehi et al., 2024). For instance, Tukel et al. (2006) studied the impact of resource tension and network complexity on buffer determination and proposed an improved RSEM. Bie et al. (2012) analysed the influence of dependencies between activities on project duration and proposed a calculation method for a buffer size. Ghoddousi et al. (2017) studied indicators, such as project flexibility, complexity, robustness and dependency, and established a buffer size calculation method that considered internal and external risks. She et al. (2021) determined the buffer size based on the analysis of the structure of the project network. Some scholars also study project uncertainty. Luong Duc and Ohsato (2008) applied fuzzy theory to analyse the uncertainty of activity and project duration and converted it into a definite duration to ensure the reliability of the safe time estimation of each activity. Bakry et al. (2016) proposed an algorithm for optimal scheduling of repetitive construction projects under uncertain conditions and used fuzzy theory to model uncertainties related to various input parameters. Peng and Peng (2022) introduced risk integration shock rate to describe project process uncertainty and proposed a critical chain buffer setting method based on vulnerability theory. In addition, some scholars are concerned about the cost of project resources (Hu et al., 2017). Some scholars also used machine learning to study the method for setting a project buffer. Li et al. (2022) proposed a data-driven method for setting a buffer size, used full-factor experimental design and

Monte Carlo simulation to build data sets, trained the project buffer model through support vector regression, and constantly adjusted relevant parameters.

In terms of buffer monitoring, it usually divides buffers into three areas for monitoring (Kamandanipour et al., 2023; Zhao, Hu et al., 2024). When the buffer consumption is less than 1/3 of the total planned buffer, it indicates that the project activity is performing well (in the green area), and no action is required. When the buffer consumption is between 1/3 and 2/3 of the planned buffer total, it indicates possible problems in the project activities (in the yellow area), and it is necessary to identify the causes and take countermeasures. When the buffer consumption exceeds 2/3 of the planned buffer total (in the red area), it indicates that the project activity has a problem and immediate action is needed, such as rushing to work, adjusting the scope of the project and other measures to resolve the risk of delay, in which two trigger points (green zone and yellow zone, yellow zone and red zone demarcation points) are fixed (Zhang & Wan, 2019; Zhang & Wang, 2022). Though this static method (TBMM, traditional buffer management method) is easy to operate, it does not consider the possible increase of buffer consumption with the implementation of the project, which is a trigger to error warning (Zhang & Han, 2023a). Leach (2005) comprehensively considered the relationship between project implementation and buffer consumption and proposed the RBMM (relative buffer management method) but did not give the specific setting criteria for trigger points. Bei et al. (2010) proposed that the buffer required by the project should be adjusted in real-time according to the actual situation of the unfinished project. By dividing the remaining buffer at the current moment, dynamic monitoring of the buffer can be realised by setting dynamic monitoring points. On this basis, Bei et al. (2014) studied the impact of activities on buffering and further improved the dynamic buffering monitoring method based on activity-sensitive information. Zhang and Wan (2018) analysed the relationship between project uncertainty and activities and proposed that the buffer sizing should be allocated according to the risk exposure of activities, and the buffer monitoring margin of each monitoring point should be redistributed according to the risk weight factor of activities. In addition, there are also studies on building a dynamic buffer monitoring model based on project phase attributes (Zhang et al. 2018), activity reliability (Zhang et al. 2022), and other factors.

Summarising the above research results, some deficiencies were found in the existing methods. First, buffer management is a continuous work involving the planning stage to the execution stage; buffer setting and buffer monitoring correspond to the main tasks of these two stages, respectively. Most existing methods only focus on the research of one of the tasks, and there are few methods to design the coordination of the two from an overall perspective, which is not conducive to engineering practice applications. Secondly, the buffer setting of the existing methods takes economic indicators into less consideration, including project input cost, expected project return, etc. These factors imply the concept of more buffer protection for items with high economic indicators, and this concept is often given priority consideration in actual production. Based on this, this paper developed a new method for building a multi-factor critical chain buffer estimation model and designing a dynamic monitoring method based on project elements. This method improves the efficiency of buffer setting, ensures that high-yield projects obtain more buffer guarantees under the condition of limited resources, and reduces the occurrence probability of false warnings that often occur in traditional buffer monitoring. Specifically, it will include method analysis and case operation.

2. Research methods

2.1. Influential factors of a buffer

To ensure the stability of the multi-project schedule and improve the probability of completion on time, the critical chain method absorbs the uncertainties in the execution of activities through the use of buffering. When activities are affected by multiple uncertain factors. It is necessary to analyse the relationship between the multiple factors, establish a multi-factor critical chain buffer estimation model, and then obtain the project buffer sizing through the estimation of the activity buffer so as to calculate the overall buffer size of the multi-project. The project importance, resource tension, and on-time completion probability are discussed from the perspective of project management elements.

Project importance and its measurement coefficient

According to the definition of portfolio value management (Bu et al., 2021), all portfolios need to be managed to enhance and maintain organisational value. Value is a measure of the impact achieved by an entity or service.

To measure this value, refer to the definition of net income (profit) in economics.

First, consider the project in terms of net revenue, take the product of the project's expected return and project success probability minus the input cost as the net benefit. Then, divide the net benefit of a single project by the net benefit of the whole of multiple projects to obtain the final benefit, which is defined as the importance index Qi of project i. Qi reflects the importance of a single project i in a multi-project ensemble.

$$Q_i = \frac{E_i}{E} = \frac{V_iP_i - C_i}{VP - C}, i \in [1, N] \quad (1)$$

In Formula (1), a multi-project consists of N single projects. E_i、V_i、P_i and C_i represent the income, expected return, success probability, and input cost of project i, respectively. E represents the net benefit of all projects, V represents the expected return matrix, P represents the probability of success matrix, and C is the cost matrix (generally a constant matrix). There are correlations between projects in multiple projects. For example, V_{12} represents the return from the joint implementation of Project *1* and Project *2*, P_{12} represents the probability that Project *1* and Project *2* will succeed together depending on each other.

Second, the buffer sizing should meet the expectations of project value management. The measurement of returns is an influential factor in the buffer setting. For important projects with high returns, the appropriate buffer should increase to ensure its on-time completion principle and for general projects with lower returns, excess buffers should reduce. The importance measurement coefficient is defined as follows to reflect the importance difference between projects in the buffer setting.

$$\lambda_i = 1 + (Q_i - \overline{Q}) = 1 + (Q_i - \frac{\sum_{i=1}^{n} Q_i}{n}) \quad (2)$$

In Formula (2), $\overline{Q}$ means of the importance of items in multi-project. λ_i as a product factor, when Q_i exceeds $\overline{Q}$ and λ_i is greater than 1, the buffer sizing is amplified. When Q_i is less than $\overline{Q}$, the buffer sizing is compressed.

Resource tension coefficient

The intensity of active resource usage is another factor affecting buffer setting. On this basis, according to the characteristics of multi-project multi-resource constraints, the resource tension coefficient within the activity duration is defined as follows.

$$\alpha_{w_{(i,j)}} = Max \sum_{k=1}^{K} r_{w_{(i,j)},k} / R_{k,t}\ , \quad t \in d_{w_{(i,j)}} \quad (3)$$

In Formula (3), $w_{(i,j)}$ represents the activity j of project i, $r_{w_{(i,j)},k}$ represents the demand for resource k of activity j of project i within the duration $d_{w_{(i,j)}}$, $R_{k,t}$ represents the available use of resource k at time t, and K represents the set of all resources k.

In this step, the proportion of single resource demand of all activities in multiple projects in unit time is first judged, and then, the proportion of different resources is accumulated to find the sum of the proportion of demand of activities in unit time under multiple resources. Finally, the maximum value of the entire activity duration is taken and defined as the activity resource tension. The larger the $\alpha_{w_{(i,j)}}$, the more resources are required, and the smaller the value, the less resources are occupied. In addition, when designing multi-resource demand effects, the use of summation instead of product is to consider that the product may weaken the size of the value and does not reflect the characteristics that the buffer Settings should be increased when the tension of multiple resources is high.

On-time completion probability

The probability of completing each activity on time can be expressed through PERT's three-point estimation time, namely the most optimistic completion time, the most likely completion time and the most pessimistic completion time. The ratio of the difference between the most likely time and the most optimistic time to the difference between the most pessimistic time and the most optimistic time is defined as the elasticity coefficient as follows.

$$\beta_{w_{(i,j)}} = \frac{m_{w_{(i,j)}} - a_{w_{(i,j)}}}{b_{w_{(i,j)}} - a_{w_{(i,j)}}} \quad (4)$$

In Formula (4), $a_{w_{(i,j)}}$ is the most optimistic time of project i activity j, $m_{w_{(i,j)}}$ is the most likely time, and $b_{w_{(i,j)}}$ is the most pessimistic time. When $m_{w_{(i,j)}}$ approaches $a_{w_{(i,j)}}$, it means that the activity is more likely to be completed optimistically, the smaller $\beta_{w_{(i,j)}}$ is, the greater the probability that the activity will be completed on time. When $m_{w_{(i,j)}}$ approaches $b_{w_{(i,j)}}$, it means that the activity is more likely to be completed pessimistically, the greater the $\beta_{w_{(i,j)}}$ is, the smaller the probability that the activity will be completed on time.

2.2. Multi-factor buffer estimation model

Based on the above analysis of income and the improvement of the root difference method, resource and on-time completion probability, a multi-factor capacity constraint buffer estimation model is proposed.

$$CCB = \left\{ \sum_{j \in CCB} \left[1 + \alpha_{w_{(i,j)}}\right] \cdot \beta_{w_{(i,j)}} \cdot \lambda_i \cdot (b_{w_{(i,j)}} - m_{w_{(i,j)}})^2 \right\}^{\frac{1}{2}} \tag{5}$$

$$CCB_i = \left[\sum_{j \in CCB_i} m_{w_{(i,j)}} / \sum_{i \in CCB} \sum_{j \in CCB_i} m_{w_{(i,j)}} \right] \cdot CCB \tag{6}$$

In Formula (5) and Formula (6), $\alpha_{w_{(i,j)}}$ and $\beta_{w_{(i,j)}}$ are the resource tension and on-time completion of activity j of Project I, respectively, λ_i is the measurement coefficient of importance of Project i, and activity j in all i is equal to this value. It can be seen that the improved *CCB* takes the activities involved on the critical chain of the system as the unit of calculation, and the final buffer size is obtained after summating and taking the root. *CCB* is the set of all activities on the critical chain of the system, and CCB_i is the set of activities that use bottleneck resources from the first to the last of Project i on the critical chain of the system. Its size is assigned according to its proportion of the most likely completion time on the critical chain of the system.

2.3. Buffer monitoring point setting

After completing the buffer position setting, the monitoring study of the project execution began. First, the health of the overall progress at a given moment is determined by the consumption of the buffer at that moment.

$$BU_{j \in CC,t} = AT_{j,t} - PT_{j,t} = \sum_{k=1}^{j} (AT_{k,t} - PT_{k,t}) \tag{7}$$

In Formula (7), $AT_{j-1,t}$ is the actual cumulative construction period that has occurred before activity j (including activity j) on the critical chain of the system at time t, $PT_{j,t}$ is the planned cumulative construction period before activity j (including activity j) at time t, and the difference between the two is defined as the buffer consumption $BU_{j \in CC,t}$ before activity j (including activity j). If $BU_{j \in CC,t}>0$, it indicates that the actual construction period is greater than the planned period, the progress is delayed, and the buffer is being consumed. If $BU_{j \in CC,t} \leq 0$, it indicates that the actual construction period is less than or equal to the planned construction period, the progress is ahead of schedule or normal, and the buffer is not consumed.

Second, compare the difference between the actual buffer consumption and the total buffer reserve, evaluate the buffer amount needed after the moment, and set the dynamic buffer monitoring point.

$$BR_{j \in CC,t} = PB_{j \in CC,t} - BU_{j \in CC,t} \tag{8}$$

In Formula (8), $BR_{j \in CC,t}$ is the remaining buffer after activity j at time t, and $PB_{j \in CC,t}$ is the total buffer reserve. When $BR_{j \in CC,t} \leq 0$, $BU_{j \in CC,t} \geq PB_{j \in CC,t}$, it means that buffer reserve has been exhausted and the project has been delayed. At this time, it is no longer meaningful to study the buffer monitoring settings, so this paper analyses the situation based on $BR_{j \in CC,t}>0$, $BU_{j \in CC,t} < PB_{j \in CC,t}$. Refer to Goldratt's definition of buffer monitoring area division to divide the monitoring area. Since the value of buffer consumption $BU_{j \in CC,t}$ may be positive or negative, two cases are discussed. When $BU_{j \in CC,t}>0$, $BR_{j \in CC,t}<PB_{j \in CC,t}$, the buffer is consumed, and the remaining buffer is the total buffer reserve minus the actual buffer consumption. Accordingly, dynamic monitoring point 1 and monitoring point 2 are set. When $BU_{j \in CC,t} \leq 0$, $BR_{j \in CC,t} \geq PB_{j \in CC,t}$, the buffer is not consumed, and the remaining buffer is the total buffer reserve. Dynamic monitoring point 1 and monitoring point 2 are set for this value. In addition, the absolute value of the actual buffer consumption, that is, the set of pre-completed quantities up to and including activity j at time t, can be regarded as an additional supplement to the total buffer reserve, the specific setting method of which is not discussed in this paper.

Based on the above analysis, the buffer monitoring point settings for activity $j+1$ are defined as follows.

Monitoring point 1： $BM1_{j+1 \in CC,t}$ =

$$= \begin{cases} BU_{j \in CC,t} + \frac{1}{3} BR_{j \in CC,t}, & BU_{j \in CC,t} \geq 0 \\ \frac{1}{3} PB_{j \in CC,t}, & BU_{j \in CC,t} < 0 \end{cases} \tag{9}$$

Monitoring point 2： $BM2_{j+1 \in CC,t}$ =

$$= \begin{cases} BU_{j \in CC,t} + \frac{2}{3} BR_{j \in CC,t}, & BU_{j \in CC,t} \geq 0 \\ \frac{2}{3} PB_{j \in CC,t}, & BU_{j \in CC,t} < 0 \end{cases} \tag{10}$$

Third, according to the setting of dynamic monitoring points $BM1_{j+1 \in CC,t}$ and $BM2_{j+1 \in CC,t}$, classification processing is as follows. When $BU_{j+1 \in CC,t} < BM1_{j+1 \in CC,t}$, project execution is normal, and no action is required. When $BU_{j+1 \in CC,t} \geq BM1_{j+1 \in CC,t}$ and $BU_{j+1 \in CC,t} < BM2_{j+1 \in CC,t}$, there may be problems in project execution, and it is necessary to identify the causes and adopt countermeasures. When $BU_{j+1 \in CC,t} \geq BM2_{j+1 \in CC,t}$, project execution problems have occurred, and immediate action is needed to resolve the overall risk of delay by rushing work or adjusting the scope of the project.

Finally, based on the preceding monitoring point settings, define the dynamic monitoring procedure.

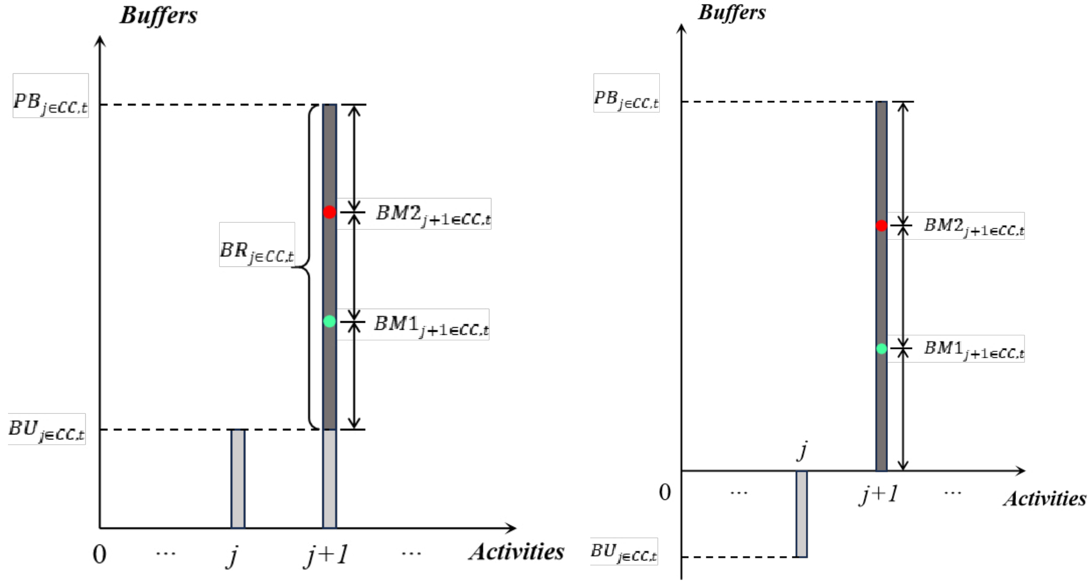

Fig. 1. Buffer monitoring point (left: when $BU_{j\in CC,t} > 0$; right: when $BU_{j\in CC,t} \leq 0$)

3. Research results and discussion

3.1 Buffer sizing calculation

A real case of a software development enterprise was used to verify the effectiveness of this paper. The company is a payment institution affiliated with a global top 500 financial group, focusing on internet payment, mobile phone payment, prepaid card issuance, and acceptance business in China. Its mobile payment transaction scale ranks among the top in the industry. In recent years, with the strong regularisation of China's financial industry and the intensification of competition within the industry, enterprises are facing a more severe market survival environment. Large internet software enterprises face challenges in internal project management. Among them, Internet IT projects have the characteristics of short duration, large quantity, and large scale (Bu et al., 2021). In the case of limited resources, they face the problem of resource conflicts among multiple projects. Moreover, project delays often occur due to an imperfect risk prevention mechanism and uncertain factors in the execution process.

In this context, three medium-sized projects carried out by the software development enterprise in the same period were selected as a verification case. The software development method adopts the "waterfall development" model. The cost input, expected return, and success probability of the project are shown in Table 1, and the working hours, activities relationships and resource requirements of each activity of the project are shown in Table 2. The resource constraints are mainly human constraints, with no more than eight development engineers and no more than four testing engineers. The critical chain of the system is 21-22-23-24-25-26-27-15-16-17-5-6-7-8-9.

According to Formulas (1) to (6), the capacity constraint buffer size CCB_i of each project is obtained, as shown in Table 3.

By summating the CCB_i values of each project, the capability constraint buffer value CCB=6.796 is obtained, and the total buffer reserve PB=6.796. Compared with the RSEM CCB_{RSEM} =8.426, the buffer size is obviously reduced, and the overall schedule is shortened.

3.2. Buffer position setting

According to the multi-project critical chain buffer setting method, the capacity constraint buffer is set at the last bottleneck resource of Project C, Project B, and Project A, respectively. Considering that the actual software projects are set in a unit of person/day, this paper set CCB_C=3, CCB_B=2, CCB_A=2, and the total capacity buffer CCB = 7. Among them, TBMM monitoring point 1: 1/3·PB = 2.27, TBMM monitoring point 2: 2/3·PB = 4.53. The monitoring points of the RBMM are monitored by two linearly increasing trigger lines; refer to Bie's method (2010) for setting (Tab.4).

Tab. 1. Summary of case project cost returns

Project	Cost C_i	Return V_i	Success PR P_i	Effect V, P	Income E_i
A	18	300	80%	$V_{A,B}$=200, $P_{A,B}$=0.9	222
B	32	800	70%	$V_{B,C}$=100, $P_{A,B}$=0.5	528
C	21	700	60%		399
ALL	71	1,800			E=1,379

Notes: Total income *E* consists of single item-income and inter-item related income. The units of Cost *C*, Return V_i and Income E_i are ten thousand yuan.

Tab. 2. Project activities hours and resources demand table (unit: person/day)

Project	Activity	Immediate activity	Work hours	50% hours	Optimistic hours	Coding engineer	Testing engineer
A	0 requirement analysis	1	3	2	1	2	0
	1 architecture design	2	2	1	1	2	1
	2 code programming	3	5	3	2	3	0
	3 self-testing	4	3	2	1	2	0
	4 smoke-testing	5	2	1	1	1	2
	5 system-testing	6	8	5	3	1	3
	6 regression-testing	7	9	5	4	1	2
	7 online release	8	2	1	1	1	1
	8 whitelist verification	9	3	2	1	0	1
	9 full open	10	3	2	1	1	1
B	10 requirements analysis	11	5	3	1	4	0
	11 architecture design	12	2	1	1	2	0
	12 code programming	13	4	2	1	4	0
	13 self-testing	14	5	4	3	5	0
	14 smoke testing	15	7	4	2	4	0
	15 system testing	16	3	2	1	2	3
	16 regression testing	17	10	7	5	2	4
	17 security scanning	18	9	6	3	1	2
	18 online release	19	4	3	2	2	1
	19 post-online verification	20	3	2	1	2	1
	20 data statistics	21	5	3	2	1	0
C	21 requirements analysis	22	4	2	1	1	0
	22 architecture design	23	2	1	1	2	1
	23 code programming	24	3	2	1	4	0
	24 self-testing	25	5	3	1	4	0
	25 system testing	26	8	5	3	1	3
	26 regression testing	27	6	4	2	1	2
	27 pressure testing	28	4	3	2	2	2
	28 online release	29	2	1	1	1	1
	29 technical support	/	3	1	1	1	1

Notes: Considering the operability of 0.5 person/day in the project and the overall program programming, 0.5 person/day is calculated as 1 person/day, the size of the optimistic working hours comes from empirical assessment.

Tab. 3. Buffer estimation parameter calculation table (unit: person/day)

I	*J*				R_1	R_2				*A*	*M*	*B*		σ	
A	0	0.161	0.277	0.884	2	0	0.250	0.000	0.250	1	2	3	0.500	1	
	1	0.161	0.277	0.884	2	1	0.250	0.250	0.500	1	1	2	0.000	1	
	2	0.161	0.277	0.884	3	0	0.375	0.000	0.375	2	3	5	0.333	2	
	3	0.161	0.277	0.884	2	0	0.250	0.000	0.250	1	2	3	0.500	1	
	4	0.161	0.277	0.884	1	2	0.125	0.500	0.625	1	1	2	0.000	1	
	5	0.161	0.277	0.884	1	3	0.125	0.750	0.875	3	5	8	0.400	3	2.039 ≈2.00
	6	0.161	0.277	0.884	1	2	0.125	0.500	0.625	4	5	9	0.200	4	
	7	0.161	0.277	0.884	1	1	0.125	0.250	0.375	1	1	2	0.000	1	
	8	0.161	0.277	0.884	0	1	0.000	0.250	0.250	1	2	3	0.500	1	
	9	0.161	0.277	0.884	1	1	0.125	0.250	0.375	1	2	3	0.500	1	
B	10	0.382	0.277	1.105	4	0	0.500	0.000	0.500	1	3	5	0.500	2	
	11	0.382	0.277	1.105	2	0	0.250	0.000	0.250	1	1	2	0.000	1	
	12	0.382	0.277	1.105	4	0	0.500	0.000	0.500	1	2	4	0.333	2	
	13	0.382	0.277	1.105	5	0	0.625	0.000	0.625	3	4	5	0.500	1	
	14	0.382	0.277	1.105	4	0	0.500	0.000	0.500	2	4	7	0.400	3	
	15	0.382	0.277	1.105	2	3	0.250	0.750	1.000	1	2	3	0.500	1	2.039 ≈2.00
	16	0.382	0.277	1.105	2	4	0.250	1.000	1.250	5	7	10	0.400	3	
	17	0.382	0.277	1.105	1	2	0.125	0.500	0.625	3	6	9	0.500	3	
	18	0.382	0.277	1.105	2	1	0.250	0.250	0.500	2	3	4	0.500	1	
	19	0.382	0.277	1.105	2	1	0.250	0.250	0.500	1	2	3	0.500	1	
	20	0.382	0.277	1.105	1	0	0.125	0.000	0.125	2	3	5	0.333	2	
C	21	0.289	0.277	1.012	1	0	0.125	0.000	0.125	1	2	4	0.333	2	2.718 ≈3.00
	22	0.289	0.277	1.012	2	1	0.250	0.250	0.500	1	1	2	0.000	1	
	23	0.289	0.277	1.012	4	0	0.500	0.000	0.500	1	2	3	0.500	1	
	24	0.289	0.277	1.012	4	0	0.500	0.000	0.500	1	3	5	0.500	2	
	25	0.289	0.277	1.012	1	3	0.125	0.750	0.875	3	5	8	0.400	3	
	26	0.289	0.277	1.012	1	2	0.125	0.500	0.625	2	4	6	0.500	2	
	27	0.289	0.277	1.012	2	2	0.250	0.500	0.750	2	3	4	0.500	1	
	28	0.289	0.277	1.012	1	1	0.125	0.250	0.375	1	1	2	0.000	1	
	29	0.289	0.277	1.012	1	1	0.125	0.250	0.375	1	1	3	0.000	2	

Notes: The columns in Table 3, from left to right: project number (*i*), activity number (*j*), Project average importance degree (), importance measurement coefficient (Q_j), number of coding engineer (r_1), number of testing engineer (r2), coding engineer tension (α1), testing engineer tension (α2), resource constraints coefficient (α), the most optimistic time (a), the most probable time (m), the most pessimistic time (b), on-time completion probability (β), *b* and *m* deviation (σ).

Tab. 4. RBMM buffer settings

Completion ratio of system critical chain (%)	**Proportion of buffer consumption**	
	monitoring point 1 (%)	**monitoring point 2 (%)**
0	15	30
100%	75	90

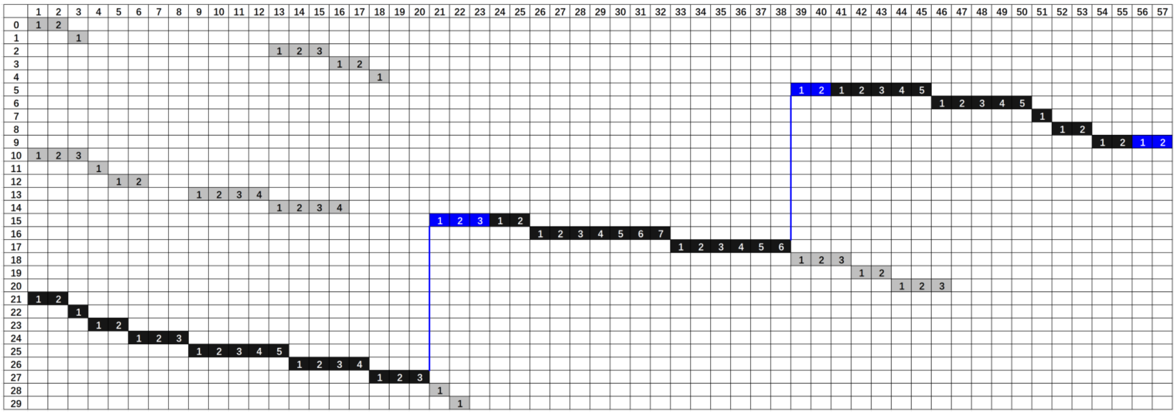

Fig. 2. Multi-project scheduling after adding capacity constraint buffer

3.3. Dynamic buffer monitoring

The simulated working hours of activities are randomly generated from the lognormal distribution (Tukel et al., 2006); the actual construction period can be simulated based on the "lognrnd()" function in MATLAB. To facilitate observation, the critical chain activities of the system were renumbered according to serial number 1 to serial number 15. Through computer programming simulation, TBMM, RBMM, and the method in this paper were respectively used for buffer monitoring. The following results were obtained in a single run.

In Figure 3, Figure 4, and Figure 5, the horizontal axis represents the activities on the critical chain of the multi-item system, and the vertical axis represents the capacity constraint buffer consumption. The blue dot represents the buffer consumption to simulate the actual activity. The green line represents the warning monitoring line 1 linked by the buffer monitoring point 1, beyond which the activity may be problematic. The red line represents the warning monitoring line 2 linked by buffer monitoring point 2, beyond which the activity has encountered problems.

By comparison, it can be found that, with the completion of activities, activity 3 to activity 15 in TBMM exceeded the warning monitoring line 1, with a proportion of more than 86 %, activity 2 to activity 7 in RBMM exceeded the warning monitoring line 1, with the proportion reaching 40 %. However, no situation beyond the monitoring line occurred in the method presented in this paper.

To verify the reliability of the above results further, the Monte Carlo technique was used to perform 1000 simulations, and TBMM, RBMM and the proposed method in this paper were analysed and compared.

Table 5, Table 6 and Table 7 show the numbers of the active buffer consumption values of the three methods that fall into the three monitoring areas. In Figure 6, Figure 7 and Figure 8, the buffer monitoring results of three methods are visually displayed in three different colours in terms of activity, buffer consumption, and execution times.

An analysis shows that the buffer consumption of TBMM does not fall into the red area in the early stage of the project, and the frequency of falling into the yellow area is also small, but the frequency of falling into the yellow area and the red area is constantly increasing in the later stage, and the frequency of falling into the yellow area and the red area reaches the highest in the last activity. This is inconsistent with the situation when the actual project goes to the later stage, and the uncertainty is smaller, as well as the warning frequency. It shows that the TBMM method does not consider the actual situation of project execution.

Compared with TBMM, the buffer warning frequency of RBMM is relatively small, but due to the linear characteristics of the relative buffer monitoring points, the lower monitoring points in the early stage lead to more warning frequency, showing a phenomenon of more before and less after. In actual work, there is generally no direct delay at the beginning of the project, and a large number of buffer warnings may cause wrong judgment of monitoring, which also indicates that the setting of RBMM monitoring points is too subjective.

The method proposed in this paper avoids TBMM and RBMM problems better, and the buffer warning frequency is the least. The buffer consumption of activities on the critical chain of the whole system is basically in the green area, and some activi-

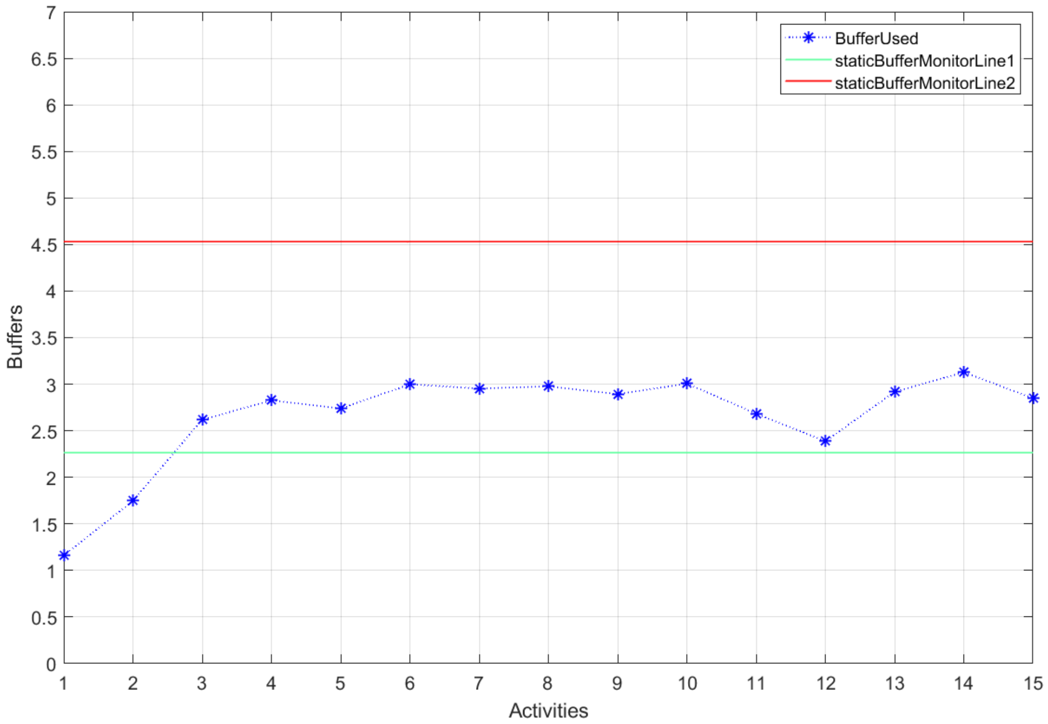

Fig. 3. TBMM method's buffer monitoring results (single time)

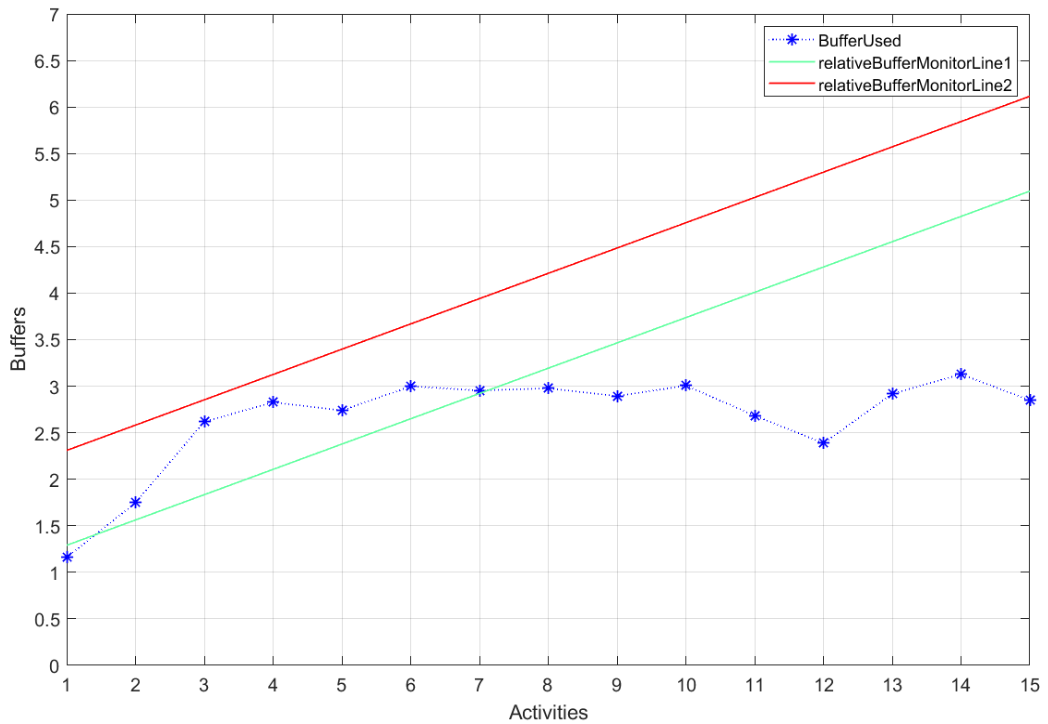

Fig. 4. RBMM method's buffer monitoring results (single time)

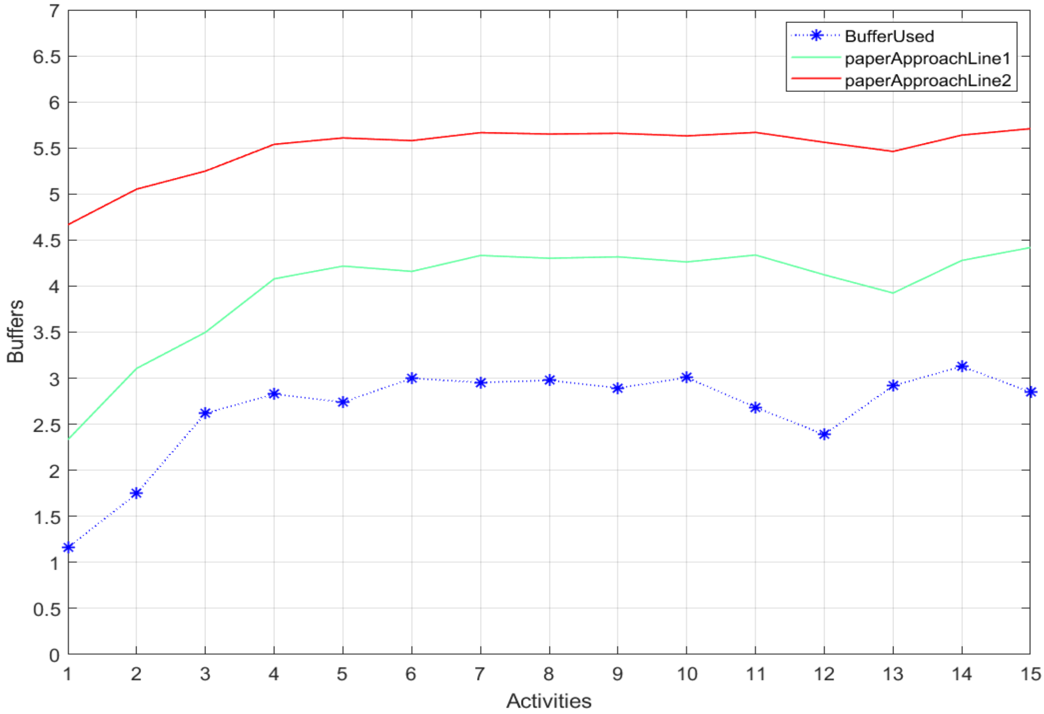

Fig. 5. Buffer monitoring results of the method described in this paper (single time)

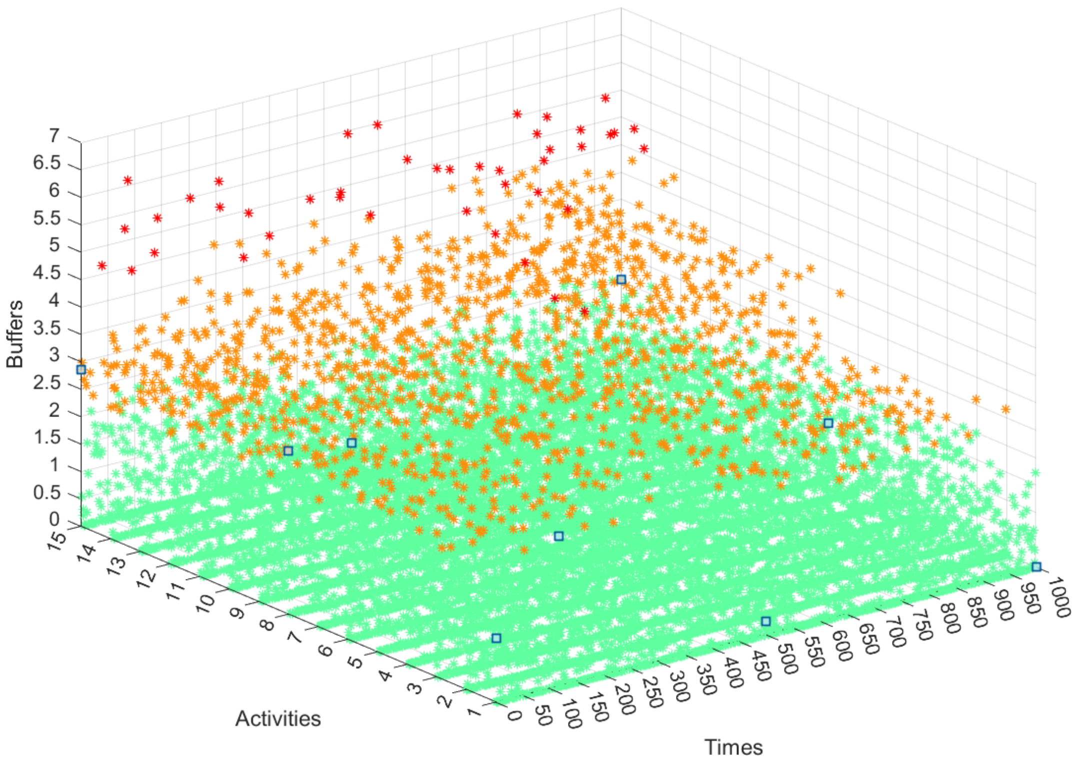

Fig. 6. TBMM method’s buffer monitoring results (1000 times)

Tab. 5. TBMM method's regional distribution of the monitoring results (1000 times)

Activities / Area	1 (21)	2 (22)	3 (23)	4 (24)	5 (25)	6 (26)	7 (27)	8 (15)	9 (16)	10 (17)	11 (5)	12 (6)	13 (7)	14 (8)	15 (9)
Less than the monitoring line 1 (green area)	997	972	951	944	948	947	915	922	916	909	896	893	885	830	820
Greater than monitoring line 1 and smaller than monitoring line 2 (yellow area)	3	27	49	56	52	53	84	77	83	90	103	105	113	154	162
Greater than the monitoring line 2 (red area)	0	0	0	0	0	0	1	1	1	1	1	2	2	16	18

Tab. 6. RBMM method's regional distribution of the monitoring results (1000 times)

Activities / Area	1 (21)	2 (22)	3 (23)	4 (24)	5 (25)	6 (26)	7 (27)	8 (15)	9 (16)	10 (17)	11 (5)	12 (6)	13 (7)	14 (8)	15 (9)
Less than the monitoring line 1 (green area)	921	911	915	932	957	976	964	974	980	987	987	995	989	990	993
Greater than monitoring line 1 and smaller than monitoring line 2 (yellow area)	76	75	75	61	41	23	32	22	19	12	12	4	10	9	7
Greater than the monitoring line 2 (red area)	3	14	10	0	2	1	4	4	1	1	1	1	1	1	0

Tab. 7. Regional distribution of the monitoring results of the method described in this paper (1000 times)

Activities / Area	1 (21)	2 (22)	3 (23)	4 (24)	5 (25)	6 (26)	7 (27)	8 (15)	9 (16)	10 (17)	11 (5)	12 (6)	13 (7)	14 (8)	15 (9)
Less than the monitoring line 1 (green area)	997	999	1000	1000	1000	1000	997	1000	1000	1000	998	999	1000	980	999
Greater than monitoring line 1 and smaller than monitoring line 2 (yellow area)	3	1	0	0	0	0	3	0	0	0	2	1	0	19	1
Greater than the monitoring line 2 (red area)	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

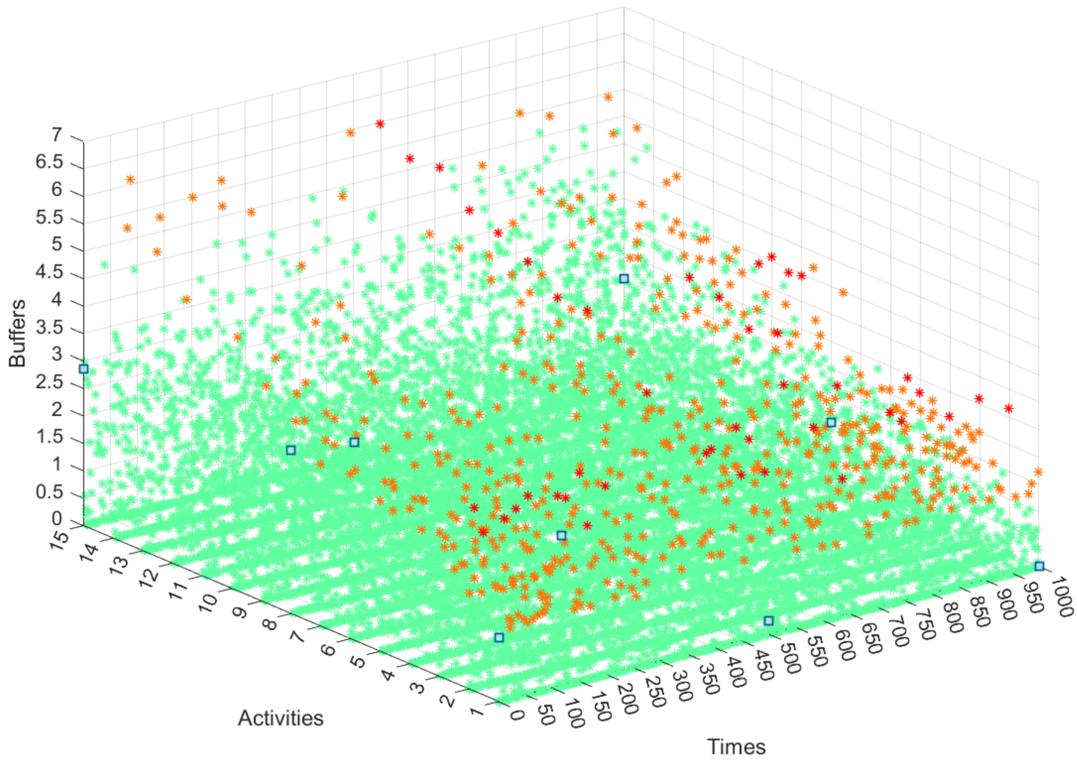

Fig. 7. RBMM method's buffer monitoring results (1000 times)

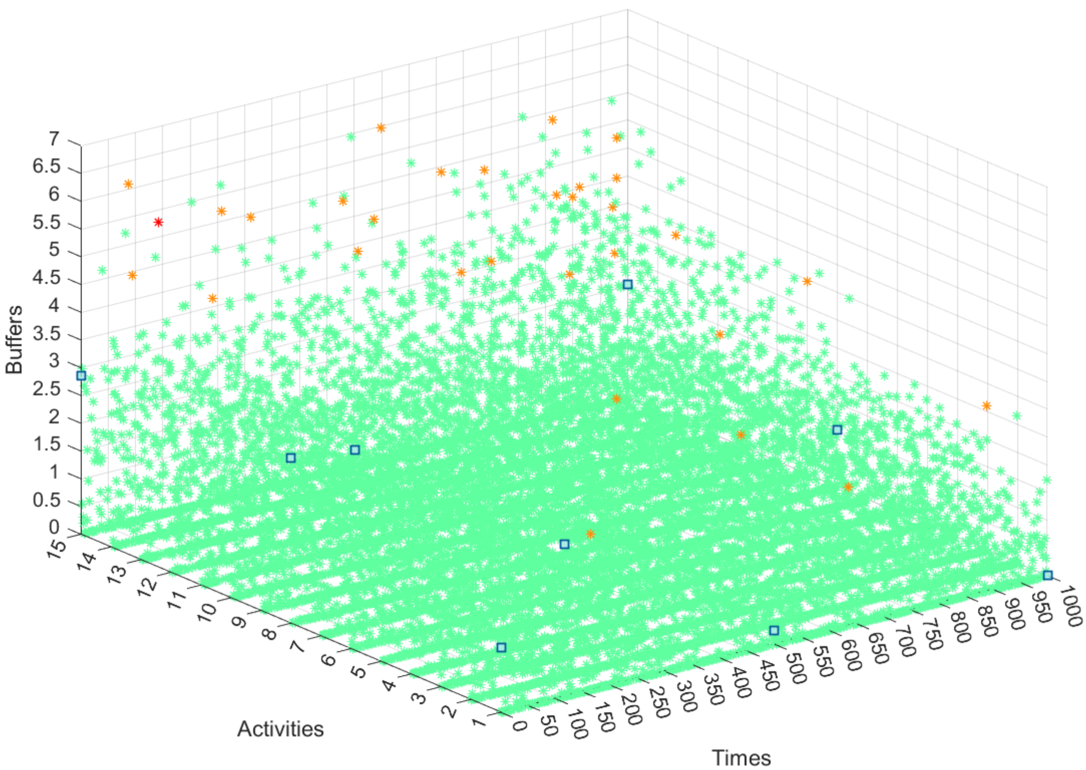

Fig. 8. Buffer monitoring results of the method described in this paper (1000 times)

ties in the yellow area are scattered, especially in the tail, due to the delay caused by uncertain factors, the buffer consumption of the last activity is processed and solved. The overall buffer monitoring cost is the best among the three methods, which obviously reduces the additional resource expenditure caused by the error buffer warning and ensures the timely completion of the multi-project execution.

Conclusions

This paper proposes a critical chain buffer setting and dynamic monitoring method based on project elements. In the planning stage, the calculation model of the multi-project capacity constraint buffer is designed by analysing three factors: project income, resources, and on-time completion probability. In the execution stage, according to the dynamic change of buffer consumption in the process of multi-project implementation, dynamic buffer monitoring points are set to monitor the buffer surplus in real-time. This method improves the efficiency of buffer setting, ensures that high-yield projects can obtain more buffer protection under the condition of limited resources, and reduces the probability of false warnings, which often occur in traditional buffer monitoring.

Managerial implications: By studying the project schedule management problem of software development enterprises under resource constraints, this paper proposes a critical chain buffer estimation model considering the influence of multiple factors from the project elements and designs a dynamic buffer monitoring model. A financial payment enterprise is taken as a case to verify the effectiveness of this method. First, in the planning stage, project importance was defined according to the input and income of multiple projects, resource tension was designed based on the activity's bottleneck resource occupation, and on-time completion probability was designed based on the PERT estimation of the activity. The capacity constraint buffer estimation model of multiple projects was established by integrating three kinds of factors, and the buffer setting size and location were determined. Second, the buffer consumption is determined according to the current activity buffer consumption, the remaining buffer is calculated through the buffer reserve, and the buffer monitoring of the next activity is dynamically set by setting dynamic monitoring points on the remaining buffer so as to achieve rolling dynamic monitoring and warning. Finally, the proposed method in this paper is verified by computer simulation with a real case, and the results are compared with TBMM and RBMM to demonstrate the effectiveness and advantages of the proposed method.

The empirical results show that compared with the traditional critical chain management method, this paper considers the characteristics of IT multi-projects under resource constraints. In terms of buffer setting, it reflects the design intention of giving priority to high-yield and high-risk projects to obtain more buffer protection and effectively shorten the overall schedule and construction period. In terms of buffer monitoring, dynamic analysis of the current buffer consumption is used to set the next activity monitoring point, and real-time prediction and judgment of buffer monitoring are carried out, which effectively reduces the occurrence frequency of false buffer warnings, makes the division of buffer monitoring area more reasonable, and significantly improves the efficiency of buffer monitoring compared with traditional methods. This paper provides a reference for the research and practice of progress assurance and monitoring in multi-project parallel software enterprises.

Limitations and further research: Limitations of this paper are reflected in two aspects: case study and buffer monitoring point settings. In terms of the case research, three software projects carried out by the enterprise within the same time period were selected. The scale of the project portfolio was relatively small and could not fully reflect the current situation of the enterprise's project portfolio. Therefore, it is necessary to expand the scope of project portfolio management and increase the scale of the project portfolio in the next step to further improve the buffer settings and monitoring methods proposed in this paper. In terms of the buffer monitoring point settings, there is no further discussion of situations where buffer consumption may be negative (such as activities being completed ahead of schedule), which can be considered as an additional supplement to buffer reserves. The buffer can be called a "pseudo-buffer"; it can appropriately reduce the dependency of the delay on the buffer amount and should be considered in dynamic buffer monitoring. Therefore, the next step is to study the influence of "pseudo-buffer" on dynamic buffer monitoring on the existing basis.

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