Hindawi
Scientific Programming
Volume 2022, Article ID 6591223, 8 pages
https://doi.org/10.1155/2022/6591223

Research Article

Calculation of Buffer Size on Critical Chain Based on Duration Distribution, Multiresource Constraints, and Relay Potential

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Received 27 December 2021; Accepted 5 March 2022; Published 27 March 2022

Academic Editor: M Pallikonda Rajasekaran

The setting of the buffer size on critical chain will impose an impact on the determination of the project duration. In order to effectively calculate the buffer size, we have comprehensively taken into account the influence of duration-related risks, multiple resource constraints, and relay potential on the buffer size of key chain in this paper, and we have enhanced the method of calculating the remaining buffer to ensure more reasonable calculation of project buffer. As a result, we can effectively calculate the buffer size in a way closer to the actual production and shorten the project duration.

1. Introduction

Critical chain project management (CCPM) is based on the critical path method with addition of the theory on constraints. Abiding by the principle of overall optimality, the method takes into account not only the execution time of the process and the logical relationship between processes but also factors of human behavior, uncertainties, and resource constraints between processes. Consequently, CCPM helps maximize the enthusiasm of personnel, reduce project schedule delays caused by student syndrome, Parkinson's syndrome, Murphy's law, etc., and effectively shorten the project duration.

The setting of the critical chain buffer is at the core of the project management of critical chains. In general, the critical chain buffer is divided into resource buffer (RB), feeding buffer (FB) and project buffer (PB). Resource buffer (RB) as an early warning for resources, feeding buffer (FB) is used to reduce the uncertainty of non-critical work, and project buffer (PB) can absorb the uncertainty in the project. The buffer zone helps eliminate the influence of the factors of uncertainties in the project on the execution plan to a certain extent. In addition, the size and the setting method of the buffer zone will directly determine the expected duration of projects.

The classical methods for determining the buffer size on critical chain mainly include the cut-and-paste method proposed by Goldratt [1]and the root variance method proposed by Newblod [2]. Herroelen and Leus [3, 4] hold that the buffer size calculated by the cut-and-paste method will increase linearly with the expansion of project scale, resulting in excessively large buffer. The root variance method is applicable to large-scale projects and depends on the experience of managers. Yang et al. [5] verified Herroelen's view through simulation, pointing out that when the number of processes is large, the cut-and-paste method appears to be too conservative, whereas the root variance method proves to be too optimistic. Furthermore, when the number of processes is medium, neither of the two calculation methods achieves high completion probability. In addition, Yang has proposed a buffer calculation method based on such attributes as the number of processes, the execution time, and the degree of flexibility during the start of project. Tukel et al. [6] proposed a method of buffer calculation while considering both resource tension and network complexity. Jiang and Chen [7] took resource constraints into account and adopted the risk assessment techniques of time risk quantity = risk probability × risk time to configure buffer zone for critical chain. Wang et al. [8] proposed a progress planning model with multiple resource constraints and analyzed each risk accordingly, improving the model of buffer calculation. Lu et al. [9] adopted the theory and method of RCPSP and used the heuristic algorithm to put forward measures of calculating buffer with free time and the resource constraints via the root variance method. Radovililsky [10] and Zhou and Feng [11] hold that the issue of determining the buffer size is equivalent to the issue of optimizing the queuing system and put forward a method of calculating the buffer size under single resource constraint by comprehensively taking into account the costs of projects. Hoel and Taylor [12] used the Monte Carlo simulation experiment to determine the size of project buffer through the expected probability of planned completion and to determine the size of the feeding buffer in accordance with the difference of free time in the activities. Rezaie et al. [13] divided the activities into three categories according to the size of the coefficient of variation of each activity and calculated the safety time with varying formulas for different types of activities. Fallh et al. [14] calculated the feeding buffer and project buffer based on the three shape parameters of the duration distribution of each activity. Long and Ohsato [15] proposed the method of fuzzy critical chain to determine the size of project buffer; Luong and Ario [16] used the fuzzy number to describe the duration of activities and adopted the method of fuzzy root variance to calculate project buffer. Zhong et al. [17] proposed the use of triangular fuzzy number to describe the uncertainties related to the duration of activities and revised the size of the feeding buffer while taking into account the characteristics of the structure of project network. Li et al. [18] used the method of fuzzy analytic hierarchy process (FAHP) to weight the six factors of process location, uncertainties related to the time of process execution, resource constraints, process complexity, process criticality, and manager's risk preference, and by using Monte Carlo simulation, they verified the feasibility and effectiveness of buffer settings. Zhang et al. [19] used the entropy weight method to evaluate uncertainties of the project, and while taking into account resource constraints, they estimated project duration. In addition, they used the fuzzy mathematics method to determine the degree of dispersion and obtained a model of buffer calculation for the project of critical chains based on the entropy weight method. Shou and Yeo [20] considered the degree of uncertainty of varying types of project activities and the risk preference of managers. Wei et al. [21] proposed a method to determine the buffer size by using the ratio of critical path length to critical chain length and the project flexibility coefficient. Cao and Liu [22] comprehensively took into account the uncertainties related to such factors as process duration, risk preference of project managers, resource constraints, complexity of process, and flexibility of project commencement and proposed a method of buffer calculation with comprehensive attribute characteristics. Tukel et al. [6] proposed a method of determining the buffer size while taking into account the degree of resource utilization and project complexity. Chu [23] proposed a method for assessing the impact of resource constraints of the project, network complexity, and managers' risk preference on the buffer size. Hu et al. [24] proposed a method of determining the buffer size of critical chain while comprehensively taking into account such factors as risks related to activity duration, resource impact coefficient, and non-critical chain residual buffer. Xu et al. [25] proposed the model of buffer setting disturbed by multiple factors such as risk preference level, resource constraints, and network complexity, which is based on the WEIBULL-BAYES linkage model of buffer dynamic adjustment and control.

The methods of improvement proposed by the above scholars are mainly based on the root variance method. These methods have taken into account such factors as the distribution of project duration, multiple resource constraints, managers' risk preferences, and flexibility of start-ups but still have limitations. (1) The activity duration risk cannot be measured in an objective way. (2) Multiple resource constraints and resource scheduling are not considered from the perspective of overall limits of resource supply in the project. (3) Given that the correction of free time difference is imported into the buffer, there will be some risks that are not included in the buffer zone. (4) Issues such as process handover and joint collaboration, cross-construction, and resource sharing are left unconsidered [26–29].

In view of the above limitations, the researchers have introduced the concept of relay potential in this paper based on existing studies and proposed a method of calculating the critical chain buffer, which comprehensively took into account the impact of activity scheduling risks, resource impact coefficients, process relay potential, and non-critical chain influx [30–32]. This method mainly features the following improvements. (1) The three-parameter β distribution is used to simulate the project duration to determine the activity safety time. (2) The influence of multiple resource constraints in the project is taken into account. (3) The influence is imposed by the process relay potential on the initial buffer size. (4) A method is proposed for calculating the remaining buffer size. (5) An improved model is proposed for calculating the buffer size in the project [33–35].

2. Factors Influencing the Buffer Size and the Model of Calculation

2.1. Method of Calculating the Impact of Duration Risks on the Buffer Size. Assuming that the process duration abides by the three-parameter β distribution, let the most optimistic time in the process be a, the most likely time be m, and the most pessimistic time be b [36–38]. Use the software of Oracle Crystal Ball (Version 11.1.2.4.000) to perform Monte Carlo simulation of the process duration. For process i, the estimated value of the duration corresponding to the 95% confidence level is $T_{95\%}$, denoted by Di, the estimated value of the duration corresponding to the 50% confidence level is

$T_{50\%}$, and the safety time of the process duration is as follows:

$$st_i = D_i - E_i. \quad (1)$$

2.2. Method of Calculating the Influence of Multiple Resource Constraints on Buffer Size. When different processes occupy multiple resources of the same type in the same time period n, the process is restricted during the utilization of resources, which is mainly constrained by resource demand r, average demand $\overline{r}$, and supply limit R. The ratio of the demand r^l and the supply limit R^l of the l^{th} resource required by process i is the resource utilization rate $\delta_i^l = r^l/R^l$. The ratio of the average demand $\overline{r}^l$ for resources to the supply limit R^l is the resource constraint coefficient $\varepsilon^l = \overline{r}^l/R^l$. The larger $\delta_i^l$and ε^l, the greater the degree of resource constraint, the greater the intensity of resource demand, and the greater the buffer required for this part. The resource impact factor R_i is as follows [7]:

$$R_i = \sum_{i\in n} \delta_i^l \varepsilon^l. \quad (2)$$

2.3. Method of Calculating the Influence of Process Relay Potential on Buffer Size

Definition 1 (see [39]). Relay potential refers to the resources available thanks to the collaboration, cross-construction, and resource allocation through the immediate work at the relay point in the relay chain network.

In the network plan of relay chain, let the relay potential of process i be Gi. When $G_i < 0$, it means that this process requires resource compensation; when $G_i = 0$, it means that this process needs no resource replenishment at all; when $G_i > 0$, it means that abundant resources are available in this process. The average speed of per capita of the scheduled construction is v:

$$v = \frac{\sum Q_i}{\sum T_i \sum_{j=1}^{n} Y_{ij}}, \quad (3)$$

where Q_i is the engineering quantity of the i^{th} process; T_i is the duration of the i^{th} process; and Y_{ij} is the number of people with the j^{th} kind of titles in the i^{th} process. While taking into account the degree of the difficulty of processes, difference coefficient among people, materials and machine in crossed construction, and usage rate of mechanical equipment, the average speed of per capita of the i^{th} process is as follows:

$$v_i = \frac{Q_i}{T_i}\eta_i, \quad (4)$$

$$\eta_i = \frac{\mu_i \varphi_i \alpha_i \text{PMN}}{\sum_{j=1}^{n} Y_{ij}}, \quad (5)$$

$$\alpha_i = \frac{\sum_{j=1}^{n} E_{ij} Y_{ij}}{\sum_{j=1}^{n} Y_{ij}}, \quad (6)$$

where η_i is the comprehensive capability index of process i; α_i is the average capability of personnel involved in process i [40]; φ_i is the efficiency coefficient of human- material-machine coordination during cross-construction of process i; M is the capacity of the equipment; N is the rate of utilization of the equipment; μ_i is the resource reserve coefficient; P is the difficulty of the process; and E_{ij} is the j^{th} title weight of the i^{th} process. The distribution table of personnel titles and weights is shown in Table 1.

3. Calculation of Buffer

3.1. Establishment of the Model of Calculating Initial Buffer. While taking into account the risk of duration, multiple resource constraints, and relay potential, the initial buffer $buffer_c$ of the c^{th} line is as follows:

$$\text{buffer}_c = \sqrt{\sum_{i\in c} \left[(1+R_i)st_i\right]^2} - \sum_{i\in c} G_i. \quad (7)$$

3.2. Setting of Import Buffer Size. When calculating the import buffer size, we need to avoid the starting time of non-critical chain coming earlier than the critical chain or the critical route changing after the feeding buffer is added. The size of the feeding buffer is set as the smaller value of the initial buffer and the free time difference, and thus the size of the feeding buffer of the c^{th} article non-critical chain is as follows:

$$FB_c = \min\left(FF_i, \text{buffer}_c\right). \quad (8)$$

The formula for calculating the free time difference in the last process i of the non-critical chain is as follows:

$$FF_i = \min_{j\in s_i}\left(ES_j - EF_i\right), \quad (9)$$

where FF_i is the free float after adding resource constraints to process i; ES_j is the earliest starting time after activity j of tight prejob i is constrained by resources; and S_i is the aggregation of all tight postactivities for activity i.

3.3. Determination of the Remaining Buffer Size. When the feeding buffer is larger than the free time difference of activities, those parts of the feeding buffer larger than the free time difference are extracted to ensure the continuous execution of processes on the critical chain. In addition, such parts of the buffer are added to the project buffer to absorb risks corresponding to this portion. Subsequently, the residual buffer is denoted as K, and by then the residual buffer K_c of the non-critical path of the c^{th} article is as follows [24]:

$$K_c = \begin{cases} \text{buffer}_c - FF_i, & \text{buffer}_c > FF_i, \\ 0, & \text{buffer}_c \le FF_i. \end{cases} \quad (10)$$

Table 1: Titles of personnel and weight distribution.

Title	Professor	Associate professor (senior engineer)	Engineer	Assistant engineer	Technicians and below
Weight	9	7	5	3	1

When the feeding process on the non-critical path of the *h article is situated at the same node, the remaining buffer is* K^*:

$$K^* = \max\left(K_1, K_2, \cdots, K_h\right). \quad (11)$$

3.4. Determination of Project Buffer Size. The calculation formula of project buffer PB under the influence of safety time, multiple resource constraints, relay potential, and residual buffer is as follows:

$$PB = \sqrt{\sum_{i\in cc} \left[\left(1 + R_p\right)st_i\right]^2} - \sum_{i\in cc} G_i + \sum K^*, \quad (12)$$

where cc is the aggregation of critical path processes of the project.

4. Instance Analysis

4.1. Project Overview. A project network plan consists of nine jobs from A to I, and the network plan progress is shown in Figure 1. Time parameters of each work (a, b, c) are shown in Figure 1, where a is the most optimistic time, b is the most likely time, and c is the most pessimistic time. The project is constrained by three resources, and the demand and supply limits of each work resource are shown in Table 2.

4.2. Monte Carlo Simulation in search of Critical Path. The Monte Carlo simulation is carried out for each process of the project with Crystal Ball software, and 2000 times of simulation results were extracted. $T_{50\%}$ was taken as the activity time of each process, and safety time $st_i = T_{95\%} - T_{50\%}$. The progress chart of network planning after Monte Carlo simulation is shown in Figure 2. Taking process D as an example, the simulation frequency distribution diagram of process D is shown in Figure 3. Then, $T_{95\%} = 5.77$/day, $T_{50\%} = 4.13$/day, $st_D = 1.64$/day, and the critical path after Monte Carlo simulation is B-F-I.

4.3. Access to Critical Paths after Addition of Resource Constraints. When the project is constrained by resources, the progress chart of network planning is adjusted in accordance with resource constraints. The chart considering resource constraints is shown in Figure 4. The project critical path after taking into account resource constraints is B-A-D-E-I. The activity duration of the project is 24.48 days.

4.4. Calculation of Relay Potential. Take the process D and process G as examples, and D and G are considered the prework of node 5. Staffing of process D includes one senior engineer, one engineer, one assistant engineer, and three technicians. Staffing of process G includes one engineer, one assistant engineer, and four technicians. Technical difference coefficient of alternate construction and personnel cross-construction of each process $\varphi = 0.90$. Difficulty of the processes is as follows: $P_D = 0.90$, $P_G = 0.8$. Equipment allocation rate of processes D and G is as follows: $M_D = M_G = 0.95$. Equipment utilization rate is as follows: $N_D = N_G = 0.95$. Planning time of processes D and G is as follows: $T_D = 4.13$d, $T_G = 5.11$d. Average speed of the relay network $v = 2.01$; then, $v_D = 2.67$, $v_G = 2.13$. According to Table 2 shown in the literature [39], the following can be observed.

When $v_D > v_G > v, T_D < T_G, [(v_D - v)T_D + (v_G - v)T_G]/v_G > T_G - T_D$, $G_D = [(v_D - v)T_D + (v_G - v)T_G - v_G(T_G - T_D)]/(v_D + v_G)$, $G_G = (T_G - T_D) - [(v_D - v)T_D + (v_G - v)T_G - v_G(T_G - T_D)]/v_D + v_G$, then $G_D = 0.26$, $G_G = 0.72$. Similarly, relay potential of other processes is calculated. The network progress planning of relay potential is shown in Figure 5. The two-way dashed line in the figure indicates the process of collaboration and resource allocation in the immediate work.

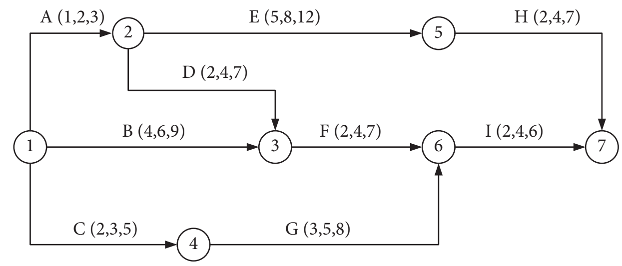

Figure 1: Progress chart of network planning.

Table 2: Demand and supply limits for each work resource.

Job number	A	B	C	D	E	F	G	H	I	Resource supply limits
Resource 1	4	6	2	2	5	3	4	4	3	8
Resource 2	1	0	0	1	1	0	0	0	1	1
Resource 3	1	1	0	1	1	1	1	1	0	2

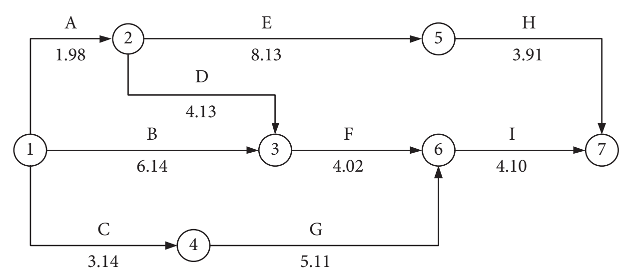

Figure 2: Progress chart of network planning after Monte Carlo simulation.

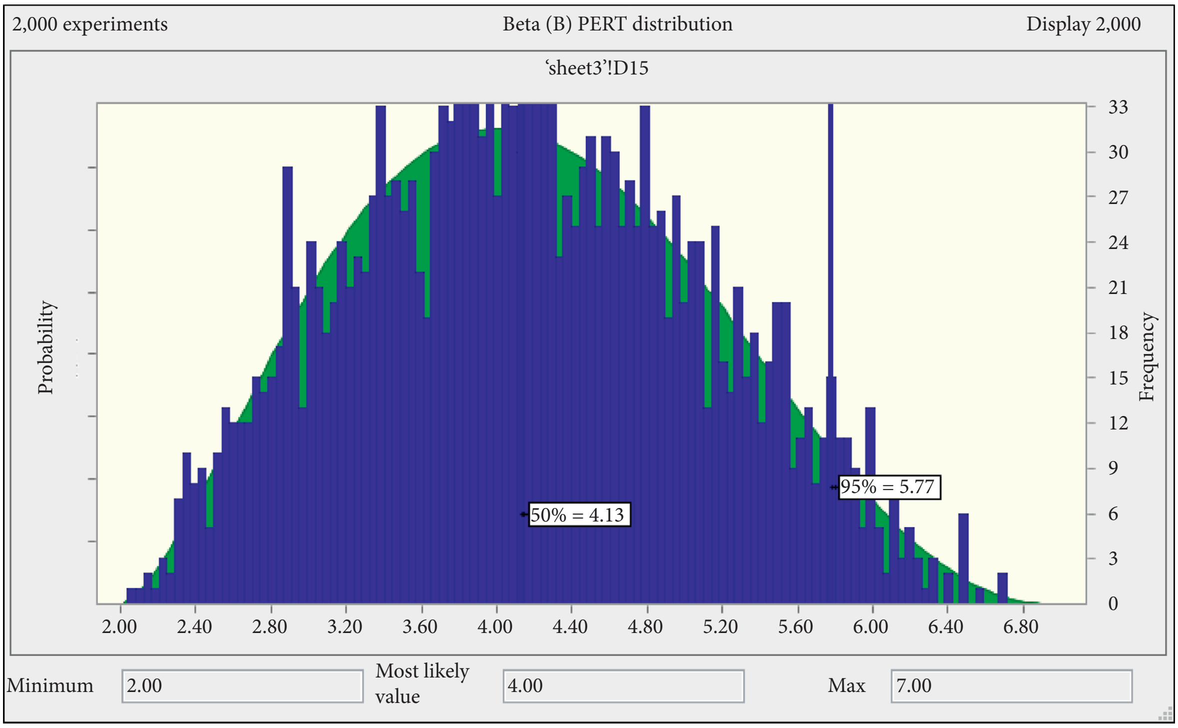

FIGURE 3: Simulation frequency distribution of process D.

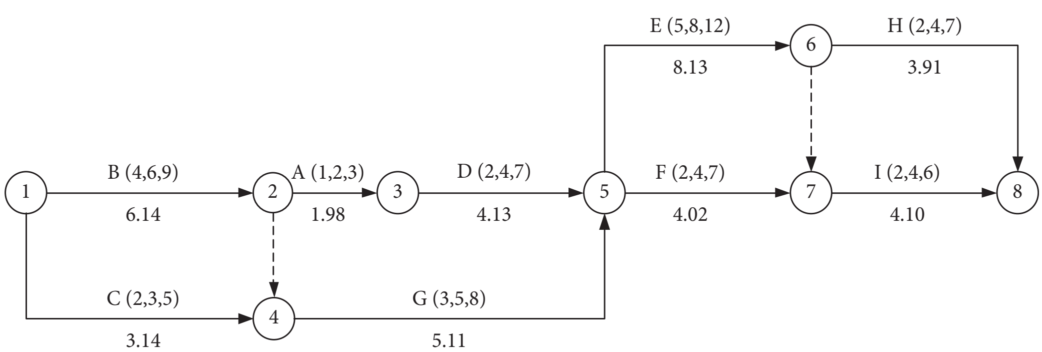

FIGURE 4: Progress chart of network planning with resource constraints in mind.

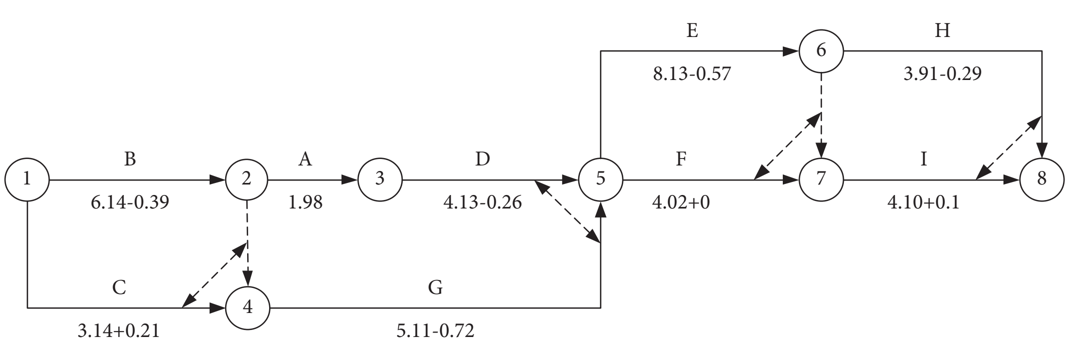

FIGURE 5: Progress chart of network planning in relay chain.

4.5. Calculation of the Buffer. Taking G as an example, the initial feeding buffer of the project is calculated to be 2.26 days according to formulas (1)–(5). The remaining buffer of 1.26 days in process G is calculated by formulas (6)–(11). According to formula (10), the project buffer is 5.97 days, as shown in Table 3.

Table 3: Buffer calculation.

Type of activities	Serial number of activities	Activity number	Three-parameter β distribution	b-m	Median ($T_{50\%}$)	$T_{95\%}$	Safety time st_i	Resource impact coefficient R_i	Relay potential G	Free float FF	The initial buffer B	The remaining buffer K	Feeding buffer FB	Project buffer PB
	1	A	(1, 2, 3)	1	1.98	2.63	0.65	1.48		0				
	2	B	(4, 6, 9)	3	6.14	7.8	1.66	0.59	0.39	0				
Critical chain activity	4	D	(2, 4, 7)	3	4.13	5.77	1.64	1.36	0.26	0	4.71			5.97
	5	E	(5, 8, 12)	4	8.13	10.4	2.27	1.54	0.57	0				
	9	I	(2, 4, 7)	3	4.1	5.75	1.65	1.17	−0.1	0				
	3	C	(2, 3, 5)	2	3.14	4.18	1.04	0.11	−0.21	3				
Non-critical chain activity	7	G	(3, 5, 8)	3	5.11	6.81	1.7	0.48	0.72	1	2.26	1.26	1	
	6	F	(2, 4, 6)	2	4.02	5.22	1.2	0.42	0	4.14	1.7	0	1.7	
	8	H	(1, 4, 6)	2	3.91	5.33	1.42	0.48	0.29	0.19	1.81	0	1.81	

Table 4: Comparison of buffer size and project duration of each calculation method.

Name of methods	Factors considered in the method	FB_G/day	FB_F/day	FB_H/day	PB/day	Project planning time/day
Cut and paste	Safety time of activity	1.5	1.5	1.5	7	31
Root variance method	Variance of activity	3	3	2	6.78	30.78
APRT method	Resource utilization	5.47	5.47	5.47	12.36	36.36
Huchen's method	Project duration risks and multiple resource constraints	1.15	2.87	2.65	6.44	31.11
Method used in this paper	Project duration risks, multiple resource constraints, and relay potential	1	1.7	1.81	5.97	30.45

4.6. Calculation of the Total Project Duration. The confidence of $T_{50\%}$ of each process is taken as the activity duration of each process. After adding the sum of activity time of each process in the key line into the project buffer, the total project duration lasts for 30.45 days.

4.7. Comparative Analysis. Judging from Table 3 in the literature [24] and the calculation results in this paper shown in Table 4, we may conclude that it is more objective to use Monte Carlo simulation to estimate the time of process activity than the cut-and-paste method and the root variance method. The simulation method addresses the issue that the buffer size in the paste copy method will increase linearly with the project size and cause an excessively large size of the buffer. However, the root variance method fails to estimate risks sufficiently, resulting in the incapability of the project to be completed on schedule. Compared with the resource utilization rate considered in the APRT method, the simulation method describes the impact of resources on the buffer in a more comprehensive manner. In addition, by taking into account the resource scheduling issue, the method has effectively addressed the issue of resource conflicts, which is closer to the actual project. Compared with C. Hu's activity duration risks and multiple resource constraints, the simulation method has taken into account the process relay, which is closer to the actual situation of the construction site. As a result, the method of buffer calculation is improved, and the project duration is effectively shortened.

5. Conclusion

In this paper, the researchers have improved the calculation of critical chain buffer and used the three-parameter β distribution to simulate the safety time, so as to estimate the project duration risks in a more objective manner. The resource impact coefficient is able to reflect the issues related to project resources comprehensively. When two or more processes are merged at the same node, the researchers have taken into account the relay potential of each process and added it in the buffer zone. During the calculation of the buffer size of critical chain projects, it is necessary to consider mutual cooperation among processes, cross-construction and resource sharing, etc., so as to enhance the buffer calculation method and effectively shorten the project duration.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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