# Buffer estimation in the critical chain method by considering internal and external risks

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**Abstract:** As a novel concept in project management, the critical chain method has attracted most researchers and project managers' attention in recent years. In this research, the internal and external source of uncertainty is considered simultaneously during the buffer estimation process. In order to identify the external risks of the project, the failure mode and effect analysis technique has been used. Additionally, the lognormal distribution function is utilised for stimulating activities duration as internal risk resources. Considering internal and external risks in a project will bring the results closer to real-world results. Finally, a real case study is experimented with to illustrate the effectiveness of the proposed model. Numerical instances show that the suggested buffer estimation method can be better than the traditional cut and paste method in projects. Various organisations can use the results of this research and individuals and, at the same time, facilitate project management.

**Keywords:** project management; buffer estimation; internal risk resources; external risk resources; failure mode; effect analysis.

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## 1 Introduction and literature review

One of the newest methods in project management is the critical chain method, which considers whole project limitations instead of every activity individually. Eliyahu Goldratt proposed it in 1997. One of the project manager's rigorous duties is scheduling the whole project under some limitations, such as time, budget and resource limitations. In the mentioned environments, the critical chain method can be a useful tool that considers relations between activities and constraints that must be managed. If resources in a project are infinite, the traditional critical path method and critical chain method have the same results (Leach, 2014).

Olson (1997) introduced the idea of the critical chain method in his book. In this book, he proposed that the theory of constraints (TOC) can be used for the development of applications in the projects. His first book revolutionised manufacturing by describing that TOC can be applied at the factory level. TOC is a managerial philosophy that believes in order to develop the operation of each system. First, the system's constraints should be identified, and then efforts must be focused on increasing the capacity of constraints (Ghaffari and Emsley, 2015).

During executing the project, project activities maybe last longer or shorter than what we expect. The sources may be temporarily unavailable, and new activities may be needed. The project may even be stopped for a while. A useful encounter with these uncertainties is a critical issue for project managers. During past years, much of the research in scheduling the projects have focused on developing heuristic and accurate methods for making initial practical scheduling, considering complete information and a stable environment (Hu et al., 2016).

Making the project's initial scheduling, risk evaluation, and measurement of the project's momentary function are essential steps for the life of the project. The project manager uses the project schedule to help plan, implement, and control project activities and follow up and check the project's progress (Fewings and Henjewele, 2019).

In project management, a method such as the critical path method, each activity duration is deterministic. However, in reality, this duration is not deterministic. Because in the past, project managers tried to simplify their work by using methodologies designed before the emergence of computers (Hazır, 2015).

The central concept in the critical chain method is that managers try to finish the project earlier than the estimated time and add buffers at the end of the project to protect the project against uncertainty (Thipparate, 2014). Also, the critical chain method has lots of advantages. However, some drawbacks should be investigated, one of which is a lack of attention to every aspect of risk in the project environment (Teller et al., 2014).

Hostettler et al. (2018) examined the strengths and weaknesses of the critical chain scheduling mechanism. They showed that determining the buffer size might lead to an additional time estimate for buffer size. Then, conducted a series of mathematical experiments on the Peterson information collection to identify the factors affecting project performance. Explicitly, they stated that the critical chain activities, in general, could increase the duration of the project. At the same time, a continuous updating of the baseline program could prevent this increase. This study is the first technical analysis of critical chain concepts (Hostettler et al., 2018).

The TOC was originally used only in project scheduling. The second application of TOC is to manage projects at a time when they share limited resources. Steyn (2002) compared the advantages and disadvantages of traditional project management and TOC project management. In their work, TOC's advanced approach to project scheduling under resource constraints is raised to improve the project program's robustness in a dynamic environment (Steyn, 2002). Zhang et al. (2014), using a case study, showed that the critical chain method made the quality and safety of work maximised, and the project's time and cost minimised.

Peng and Huang (2014) proposed two methods for determining the size of the buffer. Due to resource constraints and network complexity, density-consistent and resource-limited methods (Peng and Huang, 2014). Yang and Fu (2014) used the three features that exist in the projects to provide the model. The mentioned characteristics were the number of activities within the critical chain, the uncertainty of the time of activities, and the flexibility of the start time of activities. Using this interaction, they created a reverse method to determine the buffer size (Yang and Fu, 2014).

Izmailov et al. (2016) involved the floating concept in determining the buffer's size and used it to provide a model. The use of the floating concept causes the critical chain not to be displaced and does not encounter a deviation. A coefficient was also considered for resources, which was also taken into account in calculating the buffer size (Izmailov et al., 2016).

Koulinas et al. (2014) created a project scheduling technique with limited resources for decisions on allocating resources in a random network. Some features of the critical chain approach have also been considered in their research. Büchmann-Slorup (2014) performed modelling according to the critical chain approach. In the modelling performed by these two people, the buffer is generally removed and instead of floating. The method of determining the size of the buffer presented by them is also straightforward and therefore meets today's needs (Büchmann-Slorup, 2014).

Ma et al. (2019) combined critical chain technical and earned value methods in software development projects. Examining the proposed method and comparing it with traditional project management methods, it has finally been concluded that the present method has estimated more suitable buffers for the project. Additionally, it can manage the limited resources of the project better (Ma et al., 2019).

Raz et al. (2013) have thoroughly examined the critical chain method and the necessary explanations of this method. Then, they discuss how to implement the concept of critical chain. In this article, after introducing the critical chain method's main elements, the risk and manner of buffer evaluation in the critical chain method are examined. Finally, financial analysis is performed when implementing the critical chain concept in project management (Raz et al., 2003).

Ma et al. (2014) have presented an improved method of the critical chain in construction projects. The method presented in this study provides fewer buffers than the buffers estimated by the critical chain method alone. Also, in the model presented in this research, the source's level in the project is discussed. Finally, by implementing the proposed method, they have concluded that the proposed method has estimated fewer buffers for the project. Moreover, at the same time, it has shown good robustness in uncertainty conditions (Ma et al., 2014).

Ghaffari and Emsley (2015) have conducted a comprehensive study of the critical chain method. The study also discusses the evolution of the critical chain method. It examines the various methods by which project buffers can be estimated. Finally, various areas of the critical chain that researchers can research in the future are mentioned.

Ashtiani et al. (2007) criticised the traditional method of estimating buffer size in the critical chain method, in which 50% of the activity duration is added to the end of the project. In the method presented in their research, lognormal distribution has been used to estimate durations' length. The results show that the method presented by them has better results than previous estimating buffer size (Ashtiani et al., 2007).

Ash and Pittman (2008) proposed a heuristic method to measure buffers, including project risk. In this research, a combined method based on the PERT method has been used to estimate the project's buffer size (Ash and Pittman, 2008). Iranmanesh et al. (2016) proposed a combined method for estimating buffer size based on the post density method. Various risk criteria were considered. The method presented in their research was compared with other buffer estimation methods, and its superiority was proved (Iranmanesh et al., 2016). Mazzuto et al. (2017) proposed a fuzzy theory for project scheduling. For the first time in their research, the concept of critical chain and fuzzy theory has been used to schedule the project (Mazzuto et al., 2017).

Bregman (2011) examines the uncertainty in the time of activities on large-scale projects. Because in large-scale projects, it is impossible to determine the time of activities accurately, it is suggested that time buffers be used to deal with uncertainty. Because initial planning often changes under uncertainty, this study uses a new method to create time buffers in projects. It provides promising results (Bregman, 2011).

Salehzadeh and Mahmoudabadi (2018) considered the time of implementation of activities in the project as fuzzy numbers. The objective function of this study was to minimise the cost and completion time of the project. Based on this problem's constraints, a nonlinear mathematical model was proposed for the problem. Then, a method for linearising the model was proposed. Based on the sensitivity analysis results, a threshold for the completion time of the project is also provided. The results of the research were tested in one of the cities of Iran, and the results show that the use of the proposed method has reduced the cost and completion time of the project (Salehzadeh and Mahmoudabadi, 2018).

Zohrehvandi and Khalilzadeh (2019) have presented a method for estimating the buffer size using the failure mode and effect analysis (FMEA) method. This method in scheduling wind turbines shows that this method has been more efficient than traditional methods. In this research, to schedule wind turbines, for the first time, one of the methods of risk assessment and buffer size estimation has been studied (Zohrehvandi and Khalilzadeh, 2019).

Chauhan et al. (2017) have examined the important and influential factors in the implementation of new product production projects. After reviewing the important factors and reviewing the literature, the relationship between these factors has been investigated using the interpretive structural modelling (ISM) method. Taking these factors into account reduces project risk as much as possible (Chauhan et al., 2017).

Mirzaei and Mabin (2019) in the software development industry have compared various researches that have been done in the field of critical chain management. By studying the research, an appropriate attitude is obtained in the conditions of uncertainty and how to estimate the project's buffer size (Mirzaei and Mabin, 2019).

Jadhav et al. (2015) have examined supply chain risk. In this study, the risk is investigated in situations where the concept just in time is used. After reviewing the literature and reviewing similar research, in this research, 30 important factors that cause risk in the project are introduced in a situation where the concept just in time is used (Jadhav et al., 2015).

Zhao et al. (2020) have proposed a two-stage method for estimating buffer size with rescheduling. Due to the problems that arise when adding a buffer to the project, this research uses a two-stage approach to reduce inconsistencies as much as possible. Finally, by using simulations on many problems, the superiority of this method over previous methods has been proven (Zhao et al., 2020).

Khosravi (2019) has studied the critical chain method in the dam construction project. In this research, by comparing the critical chain management method and the critical path method, it has been concluded that the critical chain method has reduced the project completion time and has also used the resources in a better way (Khosravi, 2019).

**Table 1** Article comparison table

| *Author* | *Year* | *Buffer estimation* | *Contributions* |
|---|---|---|---|
| Hostettler et al. | 2018 | * | Project performance evaluation |
| Steyn | 2002 | | Comparison of TOC with traditional methods |
| Zhang et al. | 2014 | | Quality improvement |
| Yang and Fu | 2014 | | RSEM method introduction |
| Izmailov et al. | 2016 | * | Uncertainty durations |
| Ma et al. | 2019 | * | The flexibility of start time |
| Raz et al. | 2003 | * | Earned value method |
| Ma et al. | 2014 | * | Resource levelling |
| Ashtiani et al. | 2007 | * | Lognormal distribution for activities |
| Ash and Pittman | 2008 | * | PERT method for buffer evaluation |
| Iranmanesh et al. | 2016 | | Post density method |
| Mazzuto et al. | 2017 | * | Fuzzy theory in critical chain method |
| Present study | | * | Internal and external risks |

As can be seen from the study of previous research, so far, no research has been done in the field of the critical chain in which, in addition to the internal risks of the project, attention has been paid to the risks related to the external factors of the project. Considering the external risk factors and their analysis, the present study has tried to consider the external factors of the project in the evaluation and management of the project by the critical chain method. Considering internal and external risk factors in the project can provide more accurate results and save project resources.

In this research, new method is suggested that elaborates the internal and external sources of the risk. This article is organised as follow.

In Section 2, the proposed method is defined. The calculation of internal and external risk sources in project management is discussed. In Section 3, the proposed method and cut and paste method are compared in different risk levels. In Section 4 is the discussion of the study. Finally, in Section 5, the conclusions and future research ideas for investigations are elaborated.

## 2 Methodology

In this research, two categories for risk are considered: the internal risk of projects, and the other one is external, which occurs according to external events. The project's internal risk source in this study is uncertainty in activities duration, which has proved that the lognormal distribution function can adequately reflect this phenomenon in most situations (Hajdu and Bokor, 2014). For the external source of risk, FMEA is conducted, which is discussed in detail.

In recent years, various methods have been developed to assess risk. One of these methods is the FMEA. This method was first used for systematic risk analysis and subsequent consequences on military products, especially in the aviation industry. The most important purpose of using the FMEA method is to identify risk in system components, determine the causes, evaluate their effects on system performance, and ultimately determine ways to reduce the chances of occurrence and consequences and increase the ability to detect risk (Stamatis, 2003). In this research, due to the simplicity of use and abundant application, this method has been used to evaluate the project's external risks.

As mentioned above, in the present study, to estimate the internal risk of a project, the duration of each project activity was estimated by the lognormal distribution function. Then, to determine the riskiest external activity that may affect the completion of the project, a FMEA technique has been used according to the experts involved in the project. Ultimately, the coefficient of influence of the riskiest external activity is utilised for buffer estimation.

## *2.1 Lognormal distribution function*

As mentioned before, it is assumed that activities duration has a lognormal distribution function.

If a parameter has a lognormal distribution function, statistical properties are calculated as follow (Hajdu and Bokor, 2014):

$$E(X) = \mu_{LN} = e^{\mu+\frac{1}{2}\sigma^2} \tag{1}$$

$$\text{var}(X) = \sigma_{LN}^2 = e^{2\mu+\sigma^2}\left(e^{\sigma^2}-1\right) \tag{2}$$

$$median(X) = e^{\mu} \tag{3}$$

$$Mode(x) = e^{\mu-\sigma^2} \tag{4}$$

$$skewness = \left(e^{\sigma^2}+2\right)\sqrt{e^{\sigma^2}-1} \tag{5}$$

$$Kurtosis = \left(e^{\sigma^2}\right)^4 + 2\left(e^{\sigma^2}\right)^3 + 3\left(e^{\sigma^2}\right)^2 - 3 \tag{6}$$

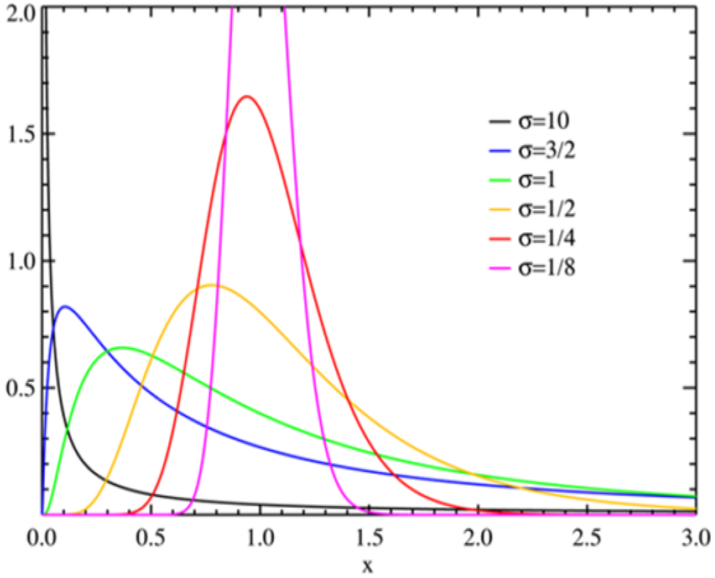
As mentioned before, the internal source of risk in this research is activities duration, whose distribution is lognormal. Skewness and kurtosis are utilised for calculating internal risk and these two mentioned properties indicate internal risk in this research. Equation (7) measures internal risk. Resource rate shows percentages at which a particular resource is available, which has values between 0 and 1.

$$Internalrisk = Resourcerate * (Kurtosis + skewness). \tag{7}$$

## *2.2 Risk parameter*

When a lognormal distribution is used in project environments, the essential matter is function parameters. Because in this study, kurtosis and skewness are used to simulate the internal risk resources, $\sigma$ plays a valuable role in this regard and is known as the risk identifier. This parameter is called the shape parameter and directly affects the distribution function shape (Hajdu and Bokor, 2014). In Figure 1 effect of on distribution, function behaviour is presented. As can be seen, if this parameter has values more than 1, the distribution function acts such as an exponential distribution function.

**Figure 1** Lognormal distribution function (see online version for colours)



In these research activities, the duration is the parameter of the distribution. For values more than 1, this function changes to an exponential distribution. As a result, values between 0 and 1 are considered as risk identifiers.

### 2.3 External risk

There are lots of external risk sources in every project whose effects are different. Some of them are important, but on the other hand, some of them can be underestimated during project management scheduling. One valuable method for finding risk effect on the project environment is FMEA (Cagliano et al., 2015). FMEA gives three properties to every risk according to project experts' judgement. These mentioned properties are as follow:

- Probability: The probability of the failure happening.
- End effect: The failure effect on the whole system.
- Detection: The means of detection of the failure mode by the manager, operator or expert.

Every property can take a number between 1 to 10, which indicates the effect of that property. Then, risk priority number can be calculated, and any risk that has maximum RPN should be considered carefully during the buffer estimation process (Cagliano et al., 2015).

$$RPN = Probability * End\ effect * Detection \tag{8}$$

After finding the most effective external risk source, the index of external risk can be calculated as follow:

$$L = RPN / 1000 \tag{9}$$

$$R = 1 + L \tag{10}$$

Finally, equation (11) is utilised for buffer estimation, which simultaneously considers both internal and external risk resources.

$$Buffersize = R * Resourcerate * (Kurtosis + skewness). \tag{11}$$

## 3 Computational experiments

C&PM method is a method initially proposed by Olson (1997). It is used as the primary method for determining the buffer size. The buffer size in this method is equal to half the sum of the secure chaining times, and the project buffer size is half the total safe-running time of the critical activity (Shou and Yao, 2000). The great advantage of this method is its simplicity. However, on the other hand, this method has shortcomings that reduce its usability. Scientists have proven that in this way, the number of activities does not have a clear effect on the completion time of the project, because in this method, the length of the buffer has a linear chain length. So, as long as the length of the chain is high, the length of the buffer becomes unreasonably long. In low-risk projects, this is an additional protection (Ghaffari and Emsley, 2015).

For comparison of the suggested method, a real project with 46 activities was selected, and the proposed method and C&PM were compared. The project understudy in the current research is related to the construction project and the related activities' timing to create a secondary route around Hamedan Province. In this study, data gathering was used by experts involved in the project, including project supervisor engineer, project control manager and civil engineer. C&PM has been executed by CCPM++ in MSP and suggested the method is programmed by VBA language in MSP 2007. Activities duration is estimated by the box Muller method, and internal risk according to equation (7) is measured.

Experts' judgements are categorised for external risks according to Table 2, and risk number priority is calculated for every category. After comparing each external risk, misassignment in financial resources is determined as the most effective external risk source in the mentioned project. For a better evaluation, the proposed method and C&PM are compared by three main indexes as follow:

1. Buffer consumption index: This index illustrates the number of buffers that are consumed in reality than the estimated buffer, which is the sum of the buffers consumed by the number of buffers (Cyplik et al., 2012).
2. Schedule violation index: This index shows the violation of schedule than the estimated value when project buffers are considered. It represents the result of dividing the actual violation time value by the scheduled time with the buffers.
3. The ratio of the number of violations in scheduling: The ratio of the number of times the actual time from the scheduled time plus the project buffer is exceeded. The ratio of the number of times that 100% of the project buffer is consumed, is considered.

Tables 3–8 are compared based on the defined indexes.

**Table 2** Expert's judgement about risk

| *Risk category* | *Row* | *Risk description* | *Probability* | *Effect* | *Risk number* | *Detection* | *RPN* |
|---|---|---|---|---|---|---|---|
| Technical risk | 1 | Inappropriate production technology | 5 | 9 | 45 | 1 | 45 |
| | 2 | Machine failure | 2 | 1 | 2 | 1 | 2 |
| | 3 | Change in product quality | 2 | 2 | 4 | 1 | 4 |
| Inner risk | 4 | Miss estimation in cost evaluation | 7 | 3 | 21 | 5 | 105 |
| | 5 | Lack of expertise | 4 | 5 | 20 | 2 | 40 |
| | 6 | Lack of workers | 3 | 3 | 9 | 2 | 18 |
| Management risk | 7 | Proposed reforms | 3 | 3 | 9 | 6 | 54 |
| | 8 | Unsettlement in project | 1 | 4 | 4 | 2 | 8 |
| | 9 | Lack of experienced project manager | 3 | 5 | 15 | 5 | 75 |
| | 10 | Change in responsibilities | 5 | 2 | 10 | 2 | 20 |
| Outer risk | 11 | Misassignment in finance resources | 8 | 8 | 64 | 6 | 384 |
| | 12 | Disordering in raw material preparation | 1 | 7 | 7 | 5 | 45 |
| | 13 | Unexpected events | 5 | 5 | 25 | 1 | 25 |
| | 14 | Disability of contractor | 5 | 7 | 35 | 8 | 280 |
| | 15 | Delays in scheduling | 6 | 8 | 48 | 5 | 240 |
| | 16 | Change in laws | 1 | 3 | 3 | 1 | 3 |
| | 17 | strikes | 1 | 7 | 7 | 1 | 7 |

## *3.1 Comparison results*

The proposed method and C&PM have been run in MSP, and buffers sizes have been calculated. Finally, three mentioned indexes have been compared in different risk levels for better understanding as shown in Table 3.

**Table 3** Cut and paste method

| $\sigma$ | *Buffer size* | *Buffer consumption index (%)* | *Scheduling violation index* | *The ratio of the number of violation in scheduling* |
|---|---|---|---|---|
| 0.3 | 141 | 28.82 | 1.04 | 0 |
| 0.4 | 141 | 43.92 | 10.57 | 0 |
| 0.5 | 141 | 62.36 | 40.64 | 8.85 |
| 0.7 | 141 | 180.29 | 473.46 | 96.83 |

Table 3 illustrates the computational results in different risk levels. As can be seen, buffer sizes for every risk level are similar, which is one of the deficient of the C&PM methods. In low-risk environments, buffer estimation has been far from reality. As presented, 28.82% of the estimated buffer in this situation is consumed, which can show the inefficiency of C&PM. Additionally, this method has lost effectiveness in high-risk situations because it has utilised more than the estimated total buffer. As presented, buffer consumption at risk level 0.7 is 180.29%. As a result, in risky projects, C&PM is not a flexible method for buffer estimation. As mentioned, this method has the same values for the project buffer for the different risk values, which is the main flaw of the method because it is not sensitive to the project risks and results are unrealistic. As the amount of buffer consumed in the column is observed, increasing the risk index in the project, the actual amount consumed from the buffer has increased, which is more reasonable in terms of higher uncertainty. However, in higher-risk environments, the number of violations exceeds the program, which is another weak point in uncertain conditions. Table 3 shows the necessity of using new methods to estimate the buffer size in uncertain conditions of the projects.

Table 4 illustrates computational results by the proposed method. As can be seen, buffer size increases by risk and in projects involved in uncertain environments can have promising results. In the proposed method, considering both internal and external risk resources lead to realistic outcomes. As can be seen, with increasing risk parameters in the project, the estimated buffer values have increased. It indicates the sensitivity of the proposed method to the project's risk, which is the first advantage of this method compared to the known method of C&PM. This method, like the C&PM method, uses a more significant amount of buffer in real conditions, as shown in column 2, with increasing risk. The other advantage of the present method is shown in the third and fourth columns. As can be seen, in all cases, the amount of planning violations is less than the C&PM method. It indicates the accuracy of the proposed method and is closer to the real-world results.

**Table 4** Proposed method

| *σ* | *Buffer size* | *Buffer consumption index (%)* | *Scheduling violation index* | *The ratio of the number of violation in scheduling* |
|---|---|---|---|---|
| 0.3 | 60.34 | 40.62 | 5.99 | 0 |
| 0.4 | 55.01 | 45.68 | 11.46 | 0.1 |
| 0.5 | 66.01 | 50.66 | 19.8 | 1.2 |
| 0.7 | 75.02 | 57.73 | 49.64 | 13.95 |
| 0.9 | 88.03 | 66.81 | 107.95 | 40.6 |

In the following, the two mentioned manners are compared more precisely at different risk levels.

In order to more accurately compare the proposed method with the C&PM method, for each level, the comparison risk is more accurately given in Tables 5–8. In these comparisons, at each risk level, if the buffer proposed by each method is lower and simultaneously, the amount consumed from the buffer in real terms would show a better performance. In contrast, a smaller number of violations of the pre-programmed amount would be more desirable.

**Table 5** Comparison between methods in risk level 0.3

| | *Buffer size* | *Buffer consumption index (%)* | *Scheduling violation index* | *Ratio of the number of violation in scheduling* |
|---|---|---|---|---|
| C&PM | 141 | 28.82 | 28.04 | 0 |
| Proposed model | 56 | 40.62 | 7.04 | 0 |

**Table 6** Comparison between methods in risk level 0.4

| | *Buffer size* | *Buffer consumption index (%)* | *Scheduling violation index* | *The ratio of the number of violation in scheduling* |
|---|---|---|---|---|
| C&PM | 141 | 43.92 | 33.22 | 0.22 |
| PM | 68 | 45.68 | 11.46 | 0.12 |

**Table 7** Comparison between methods in risk level 0.5

| | *Buffer size* | *Buffer consumption index (%)* | *Scheduling violation index* | *The ratio of the number of violation in scheduling* |
|---|---|---|---|---|
| C&PM | 141 | 62.36 | 40.64 | 8.58 |
| PM | 82 | 82.66 | 21.11 | 1.24 |

**Table 8** Comparison between methods in risk level 0.7

| | *Buffer size* | *Buffer consumption index (%)* | *Scheduling violation index* | *The ratio of the number of violation in scheduling* |
|---|---|---|---|---|
| C&PM | 141 | 52 | 191.65 | 73.28 |
| PM | 27.34 | 88.66 | 49.64 | 13.95 |

As presented in Table 5, in risk level 0.3, the proposed method estimated a smaller buffer size and simultaneously has consumed more buffer than C&PM. Therefore, at this risk level, the proposed method proves its effectiveness. As can be seen, the scheduling violation index in the proposed model at this level of risk is more favourable. Therefore, at a low-risk level, using the proposed method is quite logical concerning the C&PM method.

Tables 6–8 have companioned two mentioned methods in other different levels.

According to Tables 6–8, as the project's risk increases, the proposed method has had a lower ratio in the number of violations in scheduling. Additionally, the buffer estimated in this method has been significantly lower, which can prove the effectiveness of this method than C&PM. The recent comparison with the remaining proposed risk levels has also been proposed, and the proposed method has been investigated. As is clear from Tables 6–8, in all cases and all of the risk factors, the proposed method is quite efficient than the method of the C&PM. In none of the cases, the method of C&PM is superior.

## 4 Discussion

In this research, the critical chain method is replaced in project management. The new method is suggested for buffer estimation. As mentioned before, both internal and external sources of uncertainty are considered simultaneously in the presented method. The presented method is conducted on the real case study and numerical comparison prepared. As can be seen, in high-risk level environments and low-level environment, the presented method has had better results. Three main comparison indexes is utilised in this research. For instance, in a high-level environment, the estimated buffer in C&PM is 141. At the same time, the proposed method has suggested 27.47, which is better than C&PM. On the other hand, the percentage of the buffer consumed in C&PM is 52 shows that most of the proposed amount has not been utilised in reality. However, the proposed method has used 88.66% of the suggested buffer.

Initially, the C&PM method was used to determine the buffer size of the project. Due to the lack of sensitivity of the C&PM method to project risks, it was felt necessary to use a method that was sensitive to risk. The issues that are causing uncertainty in real-world projects are not limited to the project's internal design. In many cases, external project factors such as machine failures that are not available to the project or changes in national laws can directly impact the completion time of projects. Therefore, to make more efficient use of the critical chain method, a procedure should be used that considers the project's external risks to be included in the estimation of the buffer size. Accordingly, the proposed method in this study and the advantages of using the critical chain method simultaneously address the internal risks and external risks of the project. As the results show, the present study's proposed method is more efficient than the conventional C&PM method. It offers closer results to the real-world.

In the present study method, using the FMEA method and collecting the opinion of experts in the proposed project, various risks that may cause inconsistency from outside the project were identified. After performing the calculations, the riskiest activity that may disrupt the project's scheduling was identified, and the risk priority number was calculated. Then, the risk priority number considered in calculating the amount of buffer in the project was considered. Additionally, it will be possible to consider external risks when estimating the buffer size in the project.

Then, for different risk values, the method used in this study was compared with the cut and paste method. According to the criteria mentioned in the previous sections, both methods were evaluated. The first superiority of the proposed method compared to the cut and paste method was that different buffer risks were calculated for different values. In contrast, the cut and paste method was not sensitive to the risks of the project. Based on the introduced evaluation criteria, the proposed method had much lower violation percentages than the cut and paste method, which proves the superiority of the proposed method of this research.

Finally, the use of the method presented in this study is sensitive to internal risks and the external risks of the project, which is the innovation presented in this research. Also, the method presented in this study estimates fewer buffers than the cut and paste method. At the same time, it has a lower number of violations of scheduling, which proves this method's superiority over the cut and paste method in the critical chain.

## 5 Conclusions

In this study, a new method for buffer estimation is presented that considers both internal and external sources of risk in project management. A real case study is considered, and activities and their relations are transferred to the Microsoft project environment. Activities duration is simulated by the box Muller method, and buffer estimation is conducted by the C&PM method by adding CCPM++ to MSP. Buffer estimation by the proposed method is done by programming in VBA, and results are reported. For comparison, some performance indexes are utilised, which can illustrate the suggested method performance. In the final analysis, as results presented in all of the instances, the proposed method has optimised final results than C&PM. The simultaneous consideration of internal and external risks in the process of estimating the buffer size yields more realistic results than the well-known C&PM method. Also, the use of experts involved in the project allows for calculating external risk buffers in the process of estimating the size of the expert's view of the calculations. This research can bring the process of project control and planning as close as possible to real conditions and prevent delays in the project. Other distribution functions for internal risk resources can experiment for future research, and other methods for external risk detection can be investigated.

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