A Comparison of Buffer Sizing Techniques in the Critical Chain Method. Case Study

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Abstract:
The presented paper is an attempt to evaluate the application of different buffer sizing methods (within the critical chain approach) to a real-life project, in order to show that it is important to choose consciously one of the existing methods. The implementation of the different approaches to the buffer sizing procedure resulted in eight unique schedules. Once all the methods were implemented, the authors of this paper stumbled upon 2 inconveniences (slack vs. buffer, splitting up buffers). Funding solution for these handicaps caused obtaining eight more schedules. In order to evaluate all the determined solutions, the authors decided to establish a simulation study. A random dataset was generated of 2000 observations using the mean and variance calculated for the probability distribution determined by three possible durations (optimistic, expected and pessimistic) given by the project team members. To validate the performance of different methods, two penalty systems were designed. The test results indicate which specific buffer sizing technique performs best in the presented case, taking into account the attitude of the decision maker. The simulation study is the proposal of a method to be applied in each case of the critical chain method application, because it makes the use of the critical chain method more effective.

Keywords: *project management, critical chain, buffers, risk management*

1. Introduction

Research concerning the buffers, determining their size and positioning was the natural consequence of the presentation in 1997 by E.M. Goldratt critical chain method [1], which is an application of his theory of constraints to the field of project management. The interdisciplinary nature of the method and its revolutionary recommendations for effective project management determined a broad interest in it by both researchers and practitioners, especially as traditional project management methods [5] often turn off to be ineffective. One of the main elements of the critical chain method is getting information from the project executors concerning safety time hidden in the estimation of each project task duration and accumulate them in the form of buffers (just a few) placed at the end of selected paths. This approach aims to ensure the minimization of the risk (understood here as the probability) of overrunning the project due date, while minimizing this due date, thus the project makespan.

Let us summarize briefly the idea of the Critical Chain Method by means of the project network example presented in Figure 1:

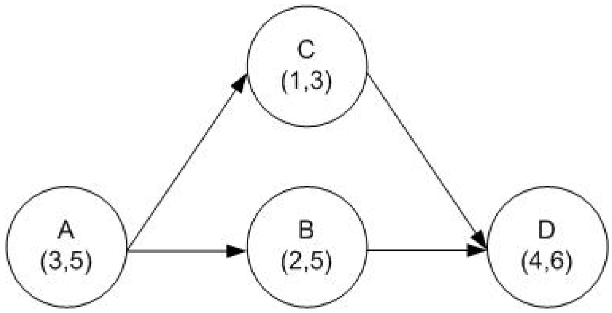

Fig. 1. Example of a project network. Source: own elaboration

Each of the four activities in Figure 1 has two duration time estimations, di95, di50, respectively the so-called safe and aggressive estimate, where the numbers 95 and 50 stand for the probability of keeping the estimate and i for the activity number and the difference between the two estimates is called safety time. Out of the two estimates, according to Goldratt, in the classical approach only the safe (greater) one is used, the aggressive one remaining unrevealed. Thus in the classical approach, the project from Figure 1 would have the estimated completion time (deadline) equal to 16 – the length of the path A, B, D with the aggressive estimates.

In the Critical Chain Method both estimates are revealed, the longest path (taking into account the availability of resources) based on the aggressive estimates is treated as the basis for the calculation of the deadline, but it is corrected by the length of a project buffer, which is considerably smaller than the difference between the longest path based on the safe estimates and that based on the aggressive estimates. However, the exact formula for the buffer may vary. In the project from Figure 1 the longest path based on the aggressive estimates has the length 9, the difference between the two longest paths is 7, thus the project buffer might be equal to 3, 5 (taking half of the difference is one of the possible approaches). Then the planned deadline of the project is determined to be equal to 12, 5. Apart from the project buffer (abbreviated PB), the shorter paths of the project network (called feeding chains) are protected by so called feeding buffers (abbreviated FB), whose length is also determined by varying formula. It needs to be said that generally the feeding chains are advised to be scheduled as late as possible, taking into account the feeding buffers. Figure 2 presents the project in question with the buffers:

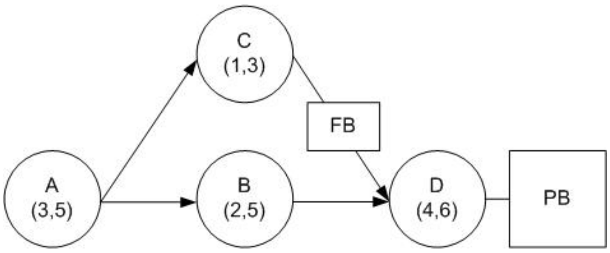

Fig. 2. Example of a project network – the Critical Chain Method. Source: own elaboration

As mentioned above, there are many methods of determining the size of buffers, however it is not known which method should be applied in which case. Also the location of buffers may vary. The methods proposed in scientific articles are described in very general terms (more as a philosophy) or they are based on the assumptions which are usually impossible to verify (e.g. that the number of activity predecessors increases the risk of the activity delay or that it is better to take for the buffer size the arithmetic average than the geometric one etc.). Each author asserts the effectiveness of their method while a few practical attempts to examine the different methods in a critical way show that the intuitions of the authors are not always reflected in reality [11]. Additionally the proposed methods are very different and often contradictory. It is obvious that different methods lead to significantly different schedules, but there is no known method of decision making in terms of choosing the right schedule in a particular case.

The aim of the paper is to propose to the reader a way of choosing the right critical chain schedule for his or her given case. The hypothesis is that in case the critical chain method is used, the choice of the buffer sizing (and location) method is important. Now, if so (and the present paper delivers kind of justification of the hypothesis, showing that it is true in one real-world case), the user needs a tool to choose the right method. In this paper we show how it can be done, by the use of simulation methods based on the EXCEL spreadsheet. The aim of the paper is not to deliver an overall evaluation of all the existing buffer sizing and location methods. Such an evaluation is still an open question, the hypothesis is that each of them may have advantages and disadvantages which depend on the very project that is being scheduled.

The present paper evaluates an application of different buffer sizing methods to a real-life project, described below, or rather to its part: the strict phase of e-office solution implementation in the district Wrocław local government.

2. Case description

The project in question is called 'The development of the ICT infrastructure in the region governed by the Wrocław district and its 7 subunits (Czernica, Jordanów Śląski, Kąty Wrocławskie, Kobierzyce, Mietków, Sobótka, Żórawina), as well as increasing availability of e-services to citizens and businesses representatives from the region of the Wrocław district'. The localities mentioned here are shown in Figure 3:

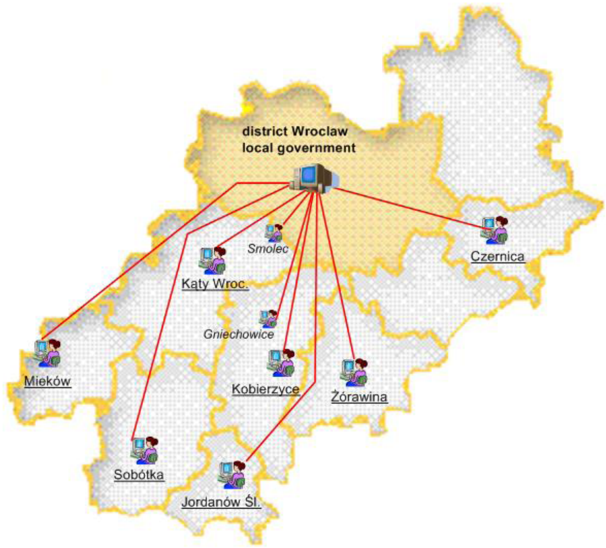

Fig. 3. The localities included in the project in consideration. Source: own elaboration

The main objective of the project is to integrate and improve the functionality of the ICT infrastructure and to introduce an integrated information system supporting the cooperation between individual units such as the district of Wroclaw and its 7 local subunits, as well as increasing the availability of electronic administrative services for the district of Wroclaw citizens.

The following sub-objectives were defined:

- Optimizing the expenses of offices, increasing the effectiveness of the unit management
- Introducing electronic services for citizens and investors
- Improving the document flow by means of the introduction of an electronic document flow system
- Improving data archiving in an electronic way
- Facilitating contact with offices and access to public information
- Improving cooperation and communication between offices and outsource units.

The population of the region governed by the district Wrocław is approximately 107,000. This is the third largest local government unit in Lower Silesia. The direct vicinity of the Wrocław agglomeration has a positive impact on the development of this area. This region is also preferable from the investment point of view. The best proof is the large concentration of businesses in the so-called Bielański Node.

The project scope is to purchase computers and software, aimed at increasing the efficiency of the officers work in the local government of the district Wroclaw and its subunits offices, hence increasing the standard of services offered to customers. The implemented solutions will enable citizens of the district Wroclaw to settle certain official matters on-line, through access to e-boxes in the offices. Furthermore, it is planned to introduce e-points in small villages and two customer service offices in Smolec and Gniechowice (Figure 3) to enable the use of the service by those customers who do not have permanent access to the Internet.

3. Literature overview

Since the very introduction of the critical chain method [1], the method has been being criticized [11] for having some significant gaps in its basic assumptions. Many attempts to improve Goldratt solution initiated the development of new approaches concerning buffer sizing techniques. However, there exists no comparative analysis or evaluation of those different techniques. The authors of this paper chose eight techniques to be compared in one real world case. A brief overview of the analyzed approaches is presented below. Once the authors of this paper had determined all the buffer sizes and created a Gantt-chart for every technique, they stumbled upon 2 inconveniences of the analyzed approaches. In order to solve these problems, the solution based on the approach proposed by Połoński and Pruszyński [9] was incorporated.

3.1. Cut and Paste 50% Method of Goldratt

Obviously the first introduced buffer sizing method was one proposed by Goldratt himself in his Critical Chain novel [1]. This method assumes that the safety time incorporated in an activity duration has to be cut-off. Then this safety time is aggregated at the end of the critical chain in the form of project buffer and as a feeding buffer wherever any noncritical chain feeds into a critical chain. The size of both types of buffers is equal to 50% of aggregated safety time of the longest path feeding into the buffer. Since Goldratt did not specify any name for that approach, Tukel *et al.* [2] referred to it as "the Cut and Paste Method" (C&PM) and Leach[3] as "the 50% of the Chain Method".

3.2. Adaptive Procedure with Density

Tukel *et al.* [2], as a counterproposal to that of Goldratt, introduce two adaptive buffer sizing methods incorporating project characteristics and level of uncertainty in the buffer size determination. The first approach, Adaptive Procedure with Density (APD), assumes that for a given number of project activities, if the number of precedence relationships increases, it is more likely that delays will occur. In such a case a delay in a particular activity execution will have an impact on all the successors of this activity. Therefore, the bigger number of precedence relationships, the bigger the buffers should be. This means that in APD the network complexity is reflected as a ratio of total number of precedence relationships of the particular activity to the total number of activities.

The feeding and project buffers sizes will be calculated in the following way:

$$BS_j = \left(1 + \frac{PRE_j}{N_j}\right) \cdot \sqrt{\sum_{i=1}^{j} \sigma_i^2}, \; j = 1, ..., J \qquad (1)$$

J – total number feeding chains and critical chain
σ_{ij}^2 – variation of an activity i in a chain j
N_j – numer of the activities in chain j
PRE_j – total number of precedence relationships defined on a chain j
BS_j – size of the buffer protecting a chain j

3.3. Adaptive Procedure with Resource Tightness

The other method introduced by Tukel *et al.*, the Adaptive Procedure with Resource Tightness [2], in order to reflect uncertainty in the feeding and critical chains incorporates in the buffer sizing process a factor called by the authors "resource tightness". The assumption was made that if the total resource usage is close to the total resource availability, it is more likely that delays will occur. Therefore, there should be larger buffers to avoid these delays. The resource utilization factor for each resource is an important parameter which is calculated as a ratio of the total resource usage and the total resource availability for each resource. Additionally, the chain standard deviation is computed assuming the applicability of the central limit theorem, which says that the mean duration of the chain is equal to the sum of the mean durations of activities making up the chain, and the variation of the chain is equal to the sum of the variations of the activities making up the chain. Hence, the feeding and project buffer sizes will be calculated in the following way:

$$BS_j = K * \sigma_j, \; j = 1, ..., J \qquad (2)$$

$$K = \frac{r}{R_{av}} \qquad (3)$$

J – total number feeding chains and critical chain
σ_j – standard deviation of a chain j
r – resource usage
R_{av} – resource availability
BS_j – size of the buffer protecting chain j

3.4. Risk Class Assessment

This buffer sizing technique takes into account the fact that activities with a large variance will have pessimistic or safe duration estimates much larger than the estimated average duration, whereas activities with a small variance will have pessimistic duration estimate close to the average duration estimates. Activities with a higher chance of having a large deviation from the average estimates should have a bigger buffer. The Risk Class Assessment technique calculates the relative dispersion (RD = standard deviation/ average duration estimate) of an activity and uses it to assign an appropriate buffer size. The relative dispersion is a measure of the uncertainty of an activity. The higher the relative dispersion, the higher the odds the activity will have a much larger duration than the average estimated duration, which implicates a higher uncertainty. The next step is to assign the activities to one of the four risk classes (A: very low uncertainty, B: low uncertainty, C: high uncertainty, D: very high uncertainty). Unfortunately the consulted sources did not provide any guideline on which ranges of relative dispersion fall within which risk class [6]. Therefore the following classification was used: RD range 0–0.13 = A; RD range 0.14 – 0.19 = B; RD range 0.20–0.25 = C; RD range 0.26–1 = D. Finally the average estimated duration of each activity is multiplied with the proposed buffer size of its risk class to generate the appropriate buffer size. After the buffer size per activity is calculated, all the buffers from the activities in a feeding chain are summed up. The total buffer is then placed at the end of the feeding chain. Table 1 provides different proposed buffer sizes for a low safety (86%), medium safety (95%) and high safety (99%) method. The medium safety and high safety methods are used in this paper.

Table 1. *Buffer sizes for different activity classes as percentages of the chain length*

Classification	Low safety	Median safety	High safety
A	4%	8%	12%
B	12%	24%	36%
C	20%	40%	60%
D	28%	57%	85%

Source: own elaboration

3.5. Original RESM

The original Root Error Square Method uses only the expected and pessimistic duration of a task in the project to determine the feeding buffers and the project buffer size. With uncertainty being the difference between the pessimistic and expected duration, standard deviation of a task equals half of the uncertainty. The standard deviation of a chain equals the root of the squares of all the standard deviations of the tasks contained in this chain.

To set the feeding buffers, it suffices to take the double of the standard deviation of the feeding chain. The project buffer equals the double of the standard deviation of the critical chain [12].

3.6. Ashtiani RESM

The Ashtiani Root Error Square Method differs from the original RESM method by one parameter. The standard deviation of individual task is calculated by dividing the uncertainty defined in section 3.5 by 1,3. As a consequence the buffers are much bigger with the Ashtiani method in comparison with the original method. This method can be considered as very safe regarding to the possibility of exceeding buffers. If reliability is of major importance, this method is recommended [10].

3.7. SSQ Method

The other approach for buffer sizing process was proposed by Leach [3]. The Square Root of the Sum of the Squares (SSQ) is very similar to the original RESM method. The difference lies in extracting the buffer sizes from the standard deviation of the branches. This method assumes that the buffer size is equal to the square root of the sum of the squares of the difference between the low risk estimate and mean estimate for each activity duration laying on the chain feeing into the buffer. The original RESM method doubles the standard deviation to obtain the buffer size, while the SSQ method sets the standard deviation as being the buffer size. In case when the feeding chain splits, only the longest chain or the largest result out of all these chains should be applied. Leach does not specify the meaning of the term 'low risk estimate'. For the purposes of the presented analysis it will be assumed that 'low risk estimate' is equivalent to 'pessimistic estimate' in the three point-estimate PERT [7].

4. Project Data

In this chapter we will present the entry data that we used in our study. The data was collected by means of document analysis and interviews. The duration times estimates were determined using various techniques advised in the literature concerning the critical chain method.

4.1. Project Network

The project network is presented in Figure 4, with the two duration estimates given under each activity node. The activity durations are presented in weeks. Since there are a few activities which can initiate the project, to simplify the overview, the dummy activity 'Start' was added. There is no dummy activity at the end of the network since a single activity (i.e. activity no. 15) terminates the project.

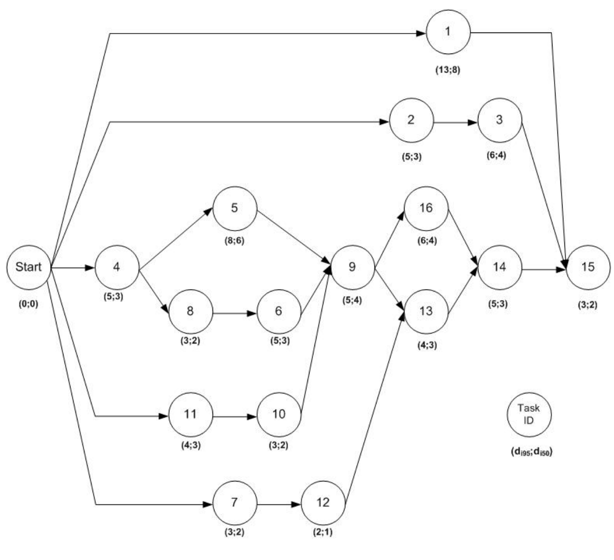

Fig. 4. Project network. Source: own elaboration

4.2. Resource

The network comprises of 16 tasks for which the durations and the resource requirements are listed in Table 2.

As it was mentioned before, 7 renewable resources are used to complete the project. Their characteristics and information about availability is presented in Table 3. The information concerning task characteristics, their resource requirements, duration estimates, as well as resource description were collected by means of interviews with project team members.

Table 2. Activities description (50% duration estimate and resource requirements)

No	Description	di50	r1	r2	r3	r4	r5	r6	r7
1	Expansion of network connections	8	3						
2	Purchase of IT equipment	3		1	1				
3	Installation of IT equipment	4	3						
4	Matching the user requirements with Telecommunication Platform (TP)	3		1	1	1			1
5	Implementing 22 four types of database	6							2
6	Implementing electronic application forms	3							2
7	Establishment of Local Certification Centre	2				1			
8	Public Information Bulletin (PIB), on-line register	2							2
9	The integration of the Telecommunication Platform, PIB, web site and HR Module	4				1			4
10	Time recording system	2					1		1
11	Implementing Human Resources Module	3					1		1
12	Purchase of digital signature	1			1	1			
13	Safety System related to the implementation of the e-office	3				2			2
14	Pilot implementation of the Telecommunication Platform	3				1		1	
15	Configuration and starting-up of hardware and software in all locations of the project	2	3			1			3
16	Training in application using	4						1	1

Source: own elaboration

Table 3. Resources description

Resource type No.	Description	Availability	Availability period
1	Technician	6	all project
2	IT Expert	1	all project
3	Procurement officer	2	all project
4	Administrator	2	all project
5	HR specialist	2	all project
6	IT coach	1	all project
7	Software developer	5	all project

Source: own elaboration

Table 4. Critical chain and feeding chains description

Chain No.	Tasks numbers	Chain duration
CC	4,5,9,16,14,15	22
1	1	8
2	2,3	7
3	6,8	5
4	11, 10	5
5	7,12,13	6

Source: own elaboration

4.3. Critical Chain Identification

For the identification of the critical chain sequence, the application cc-MPulse was used. This is an extension of the MS Project software for CC/PM method implementation. The resource use analysis (Figure 5) was also performed to verify the results given by the software.

Both approaches resulted in the same conclusion: the project critical chain consists of the sequence of tasks 4-5-9-16-14-15 and the length of the critical chain is equal to 22 weeks (i.e. only part of the total project). Additionally five feeding chains were identified (Table 4).

4.4. Buffer Sizing Techniques – Schedules

As was mentioned before, the authors of this paper decided to analyze eight buffer sizing methods, described in the previous sections. The obtained schedules, one for each technique, are depicted in the form of Gantt charts (Figures 6, 7, 24, 25, 26, 27, 28). The figures show how the project makespan and buffer sizes change from one approach to the other. Below two example figures, APD method schedule (Figure 6) and APRT method schedule (Figure 7), are presented. The others can be found in the appendix attached at the end of this paper.

The red blocks represent the activities laying on the critical chain. The grey blocks represents the other activities. The dark green blocks stand for the project buf-

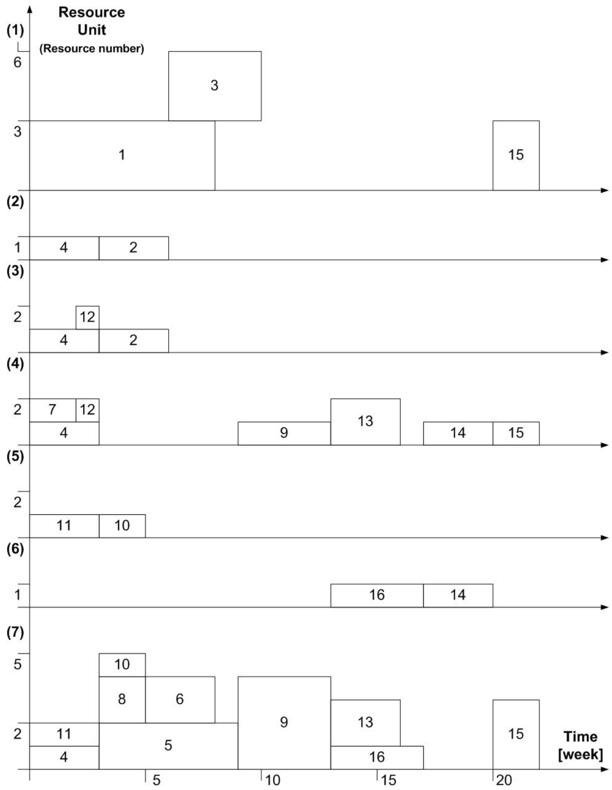

Fig. 5. Resource use profile. Source: own elaboration

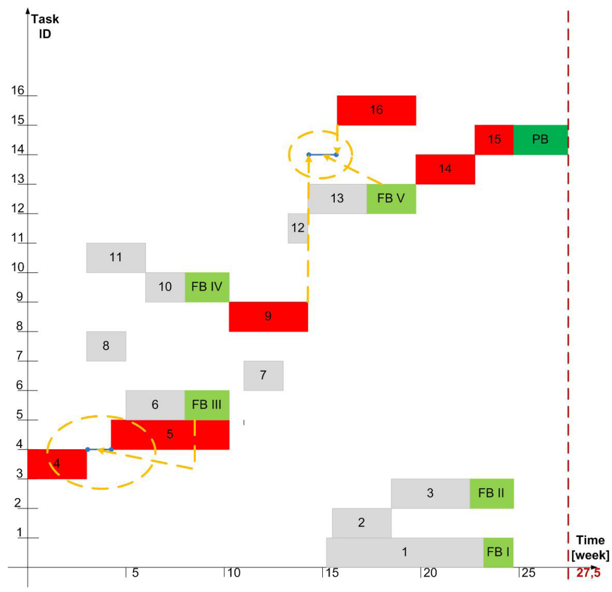

Fig. 6. APD method schedule. Source: own elaboration

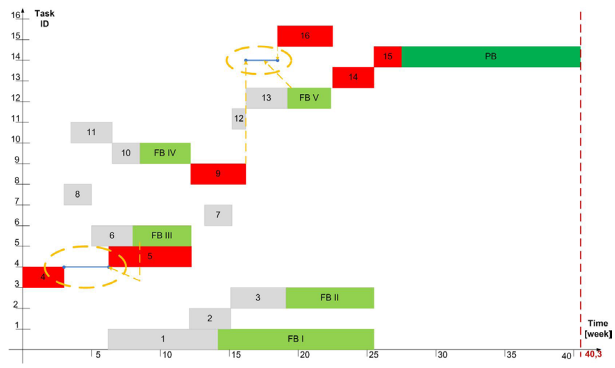

Fig. 7. APRT method schedule. Source: own elaboration

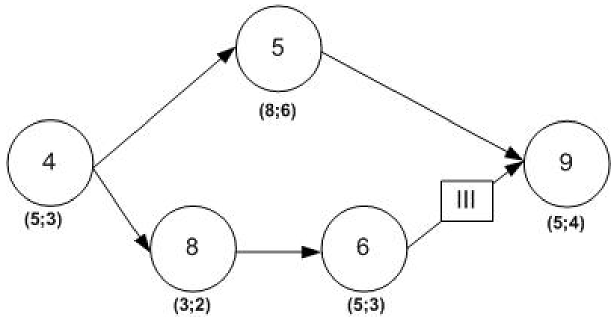

Fig. 8. Slack value versus buffer size. Part of the project network. Source: own elaboration

fer while the light green ones stand for the feeding buffers placed at the end of each feeding chain. The project due date obtained according to a particular method was marked with a red line at the end of each Gantt chart. Additionally it is important to say that breaks in the critical chain imposed by inserting feeding buffers where marked with orange circles. The analysis of the attached Gantt charts provides an overview of changes in the buffers sizes according to different techniques and the possible project due dates.

5. Buffer Location Adjustments

Once all the buffer sizes were created and a Gantt-chart for every technique was ready, the authors stumbled upon 2 inconveniences of the eight approaches. In the following paragraphs, these inconveniences will be described, explained where they are located in this particular case and how they were solved.

5.1. Slack vs. Buffer

The first inconvenience is the fact that the original methods do not take into account the slack available in every feeding chain while establishing the buffer sizes. This can result in delaying the tasks in parallel on the critical chain. This is explained by the fact that all tasks in the Critical Chain Method should be scheduled as late as possible, including the critical chain (CC). When the buffer of a particular feeding chain exceeds the slack (of that feeding chain) available, the activity(s) on the CC in parallel will be delayed by the time difference of the slack and buffer.

Table 5. Buffer III description

No	Buffer sizing technique	Buffer no 3 size	CC delay
1	Original RESM	3,61	2,61
2	Ashtiani RESM	5,55	4,55
3	Root Square	1,8	0,8
4	APD	2,25	1,25
5	APRT	4,23	3,23
6	High risk	2,52	1,52
7	Medium risk	1,68	0,68
8	Cut and paste	2,5	1,5

Source: own elaboration

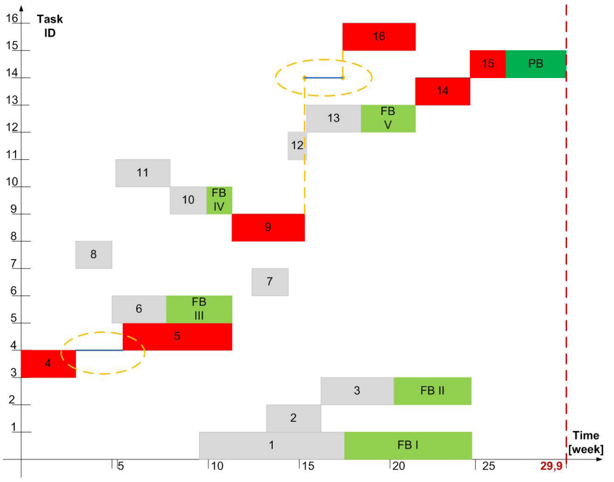

Fig. 9. RESM method schedule.Source: own elaboration

In the presented project, this was the case for the part of the network presented in Figure 8, where inside the nodes we have the numbers of activities and beneath them the aggressive estimates and the safety times of the corresponding activities. The available slack is equal to 1 (= activity 5 (d_5 = 6) – activity 8 (d_8 =2) – activity 6 (d_6 =3)) and the sizes of buffer III according to the different methods are given in Table 5. As it can be observed, the buffer according to every technique is bigger than the available slack. As a consequence activity 5, on the critical chain, will always be delayed (Table 5), which is not desirable. This delay is visualized in Gantt-chart for one of the methods (Figure 9).

As a solution, the following two changes are suggested: (1) put a maximum on the buffer size and as a maximum pick the slack available on that particular feeding chain. (2) Add the remaining of the feeding buffer to the project buffer [4]. This eliminates the delays of the activities on the critical chain and lowers the risk of the project being late. If the decision maker opted for keeping the same level of risk, he would not want to oversize the project buffer. Then he should only transfer a part of the remaining feeding buffer to the project buffer. However, which percentage should be chosen goes beyond the scope of this paper. By applying this modification to this example, for the same buffer sizing technique as in Figure 9, the modified Gantt-chart is shown in Figure 10.

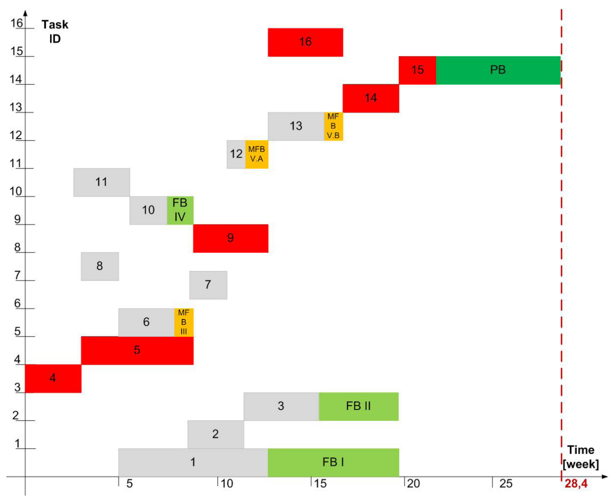

Fig. 10. Modified RESM method schedule. Source: own elaboration

5.2. Splitting Up Buffers

According to the assumption introduced by Goldratt, the buffer protecting a particular chain is placed at the end of that chain. Additionally, in this buffer all the safety time removed from the individual activities laying on a protected chain is accumulated. In the project in question, in the case of buffer no 5 this technique presents a problem. This inconvenience will be clarified now. For the better understanding of the presented below explanation, it is recommended to follow it together with the project network (Figure 3) and Figure 11. The feeding chain (7-12-13) links up with the critical chain at the end of activity 13 (Figure 11). Activity 13 can only start after activity 12 (feeding chain) and activity 9 (critical chain) are finished. Since activity 12 is scheduled as late as possible (it is one of the critical chain method assumption), it may occur that activity 9 (critical chain) has finished but activity 12 has not, which means activity 13 cannot start yet, meanwhile activity 16 (critical chain) can start. In the worst possible case this means activity 16 (critical chain) can be finished when activity 13 is not ready yet, and the critical chain will have to wait because of the delay in the feeding chain. This situation needs to be avoided. A solution for this problem is to split the original buffer up into two buffers: one before (buffer 5.A) and one after (buffer 5.B) activity 13 (Figure 10)[9]. Another difficulty here is to decide what the appropriate buffer sizes for these two new buffers should be. To tackle this problem, the original total buffer size is multiplied by a factor which is calculated as follows in the case of buffer 5.A:

factor buffer 5.A = (variance(chain(7–12)) / (variance(chain(7-12)) + variance(act 13)) + (number of activities(chain(7–12))/(number of activities(chain(7–12)) + number of activities(chain(13))) + (use of resources(chain(7–12)) / (use of resources(chain(7–12) + use of resources(act 13)))/3.

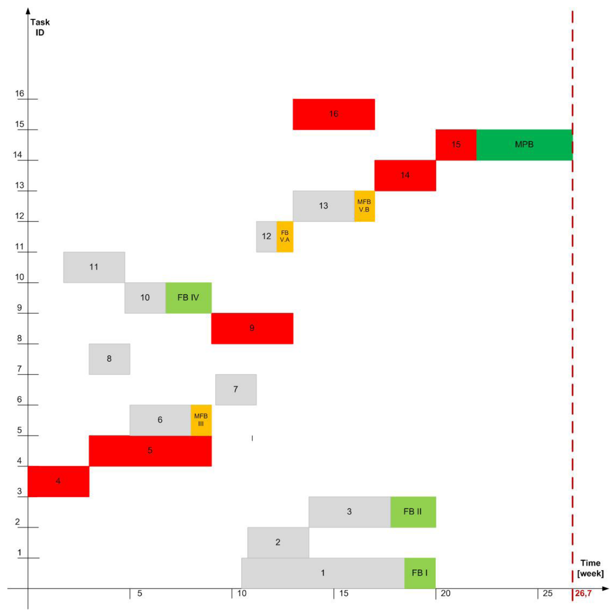

Fig. 11. Modified APD method schedule. Source: own elaboration

This formula takes into account all sources of uncertainty and risk, concerning the total project duration, in each part of the chain, and thus assigns the largest part of the original buffer to the part of the chain which carries the highest risk.

5.3. Buffer Sizing Techniques – Modified Schedules

The Gantt-charts below are a summary of the schedules with modifications. Again, for simplicity sake, only two figures will be presented below, namely the modified APD method schedule and the modified APRT method schedule. The other figures can be found in the appendix at the end of this paper.

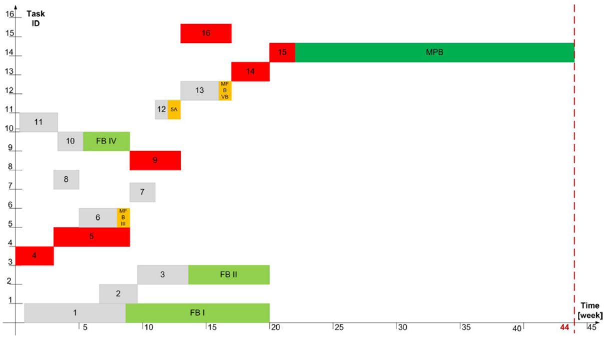

Fig. 12. Modified APRT method schedule. Source: own elaboration

The meaning of the blocks in the Gantt charts in Figures 11 and 12 is the same as before. The only thing that should be paid attention to, is the orange block, which represents the modified buffers.

6. Solution Approach

The implementation of different methods of buffer sizing resulted in obtaining eight unique schedules. In order to evaluate all the proposed solutions, the authors of this paper decided to establish a simulation study. The reason for this kind of approach is twofold. First, the analysis is made post-factum (i.e. the project is already finished) so there is no real-life evaluation possible. Second, every project is unique as well as every potential solution. Once decided to opt for a particular schedule, there is no possibility of checking the potential result of implementing the other solution in real-life conditions. A simulation which takes into account the project characteristics allows to evaluate all the possible scenarios and to propose such a buffer sizing and location method which for the very project in question ensures the best compromise between the protection against delay risk and the planned project completion time.

6.1. Creating Simulation Data

Due to lack of adequate software to simulate the application of different buffer sizing techniques, an algorithm had to be created in Microsoft EXCEL. For every task of the project an optimistic, expected and pessimistic duration were given. These estimates were obtained thanks to interviews with the team members responsible for a particular project task, conducted during the planning phase. The optimistic estimate is understood as the minimum possible time required to accomplish a task. In the project in question it is identical with the aggressive estimate (d50). The expected duration is the estimate of the time required to accomplish the task under the assumption that everything takes the usual course. In the project in question it is the same as the safe estimate (d95). As the last the pessimistic estimate was given. It is understood as the maximum possible time required to perform a task. Furthermore, it is assumed that the task duration is defined by a beta distribution. With x being the optimistic duration, y the expected duration and z the pessimistic duration, it is possible to calculate the mean and variance of these tasks using the following formulas [8].

$$m=\frac{x+4y+z}{6} \qquad (4)$$

$$\vartheta=\frac{x+4y+z}{6} \qquad (5)$$

With m being the mean and v the variance, it is possible to calculate the α and β of each task's beta distribution using the following formulas [7].

$$\alpha=m\left(\frac{m(1-m)}{\vartheta}\right)-1 \qquad (6)$$

$$\beta=(1-m)\left(\frac{m(1-m}{\vartheta}-1\right) \qquad (7)$$

With these values for α and β, 2000 random durations for each task are created according to its distribution using the EasyFit software. The sample of 2000 durations is considered big enough to reduce incorrect outcomes as a result of random data generation. This sample reflects 2000 project executions with various task durations.

6.2. Simulation Method

Combining the duration of tasks from the same chain, the total duration of the branch is determined. Using an Excel sheet it is calculated how often chain durations exceed the expected duration and, when exceeding, how deep these durations penetrate their buffers, both feeding and project buffers, using the formulas below.

IF
(chain duration < expected chain duration)⇒
"No problem" ;
ELSE
Buffer penetration = (chain duration - expected chain duration /buffer size) * 100;
(8)

It suffices to count the number of times no problem occurs and to categorize the percentage of penetration according to the selected degrees to create a histogram with the overall results. Penetration up to 33% of the feeding buffer is called "low penetration", from 34% to 66% is called 'medium penetration' and over 66% is called 'high penetration' (Figure 13).

Durations bigger than the expected duration of the chain plus the buffer are labeled as "exceeding buffer"The obtained histogram gives a clear overview of the reliability of the corresponding buffer sizing and location method.

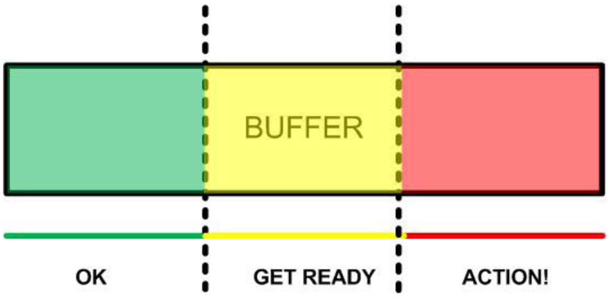

Fig. 13. Buffer penetration level. Source: own elaboration [13]

7. Buffer Sizing Techniques. Conclusions

In the following paragraphs the reader finds a brief overview of some relevant remarks and characteristics concerning the different buffer sizing techniques. There is one point requiring attention: the reader will notice that in case of some techniques there is a high risk associated with buffer 5.A (i.e. the times it exceeded the buffer was very high). However, this does not cause a problem when buffer 5.B can cope with this delay (i.e. the time left in buffer 5.B is bigger than the amount of time by which buffer 5.A has been exceeded).

7.1. Overall Performance Comparison

To compare the performance of all the techniques two penalty systems are designed. One focalizes on low risk seeking project managers whose main objective is reliable deadlines. A low risk seeker prefers a longer project planned completion time (deadline), thus a longer project buffer, so that the project deadline is more probable to be kept. At the same time, he is very unhappy about not keeping the longer deadline. The other penalty system is in favor of a high risk seeker. He wants to be competitive and prefers a shorter project completion time (deadline), thus a shorter project buffer, and at the same time he is readier (although of course not quite happy) to accept to exceed this shorter deadline. Penalty names in Table 6 are as follows: the penalty "over buffer" penalizes for every week the project duration exceeds the project critical chain plus the project buffer, thus the due date, while the penalty "Due date" is the penalty the project manager gets for every week of the project buffer (Table 6).

Table 6. Penalties description

	Penalty Low Risk	Penalty High Risk
Over buffer	40000	20000
Due date	500	1000

Source: own elaboration

Two cases were considered: that of the low risk seeker, whose main objective are reliable deadlines, a high penalty of 40 000 per week exceeding the project buffer is added and a relatively small penalty of 500 per week of project buffer. For the high risk seeker, who prefers the project planned durations, thus project buffers, to be short, but is ready to accept a higher risk of exceeding the project buffer, these costs were 20 000 and 1 000, respectively. The numbers themselves are fictitious. Only the proportion between the penalties is of any relevance.

The first case is one for a low risk seeker. The best technique for a low risk seeker to use is the Original RESM method. The high risk class method takes the second place, just behind the Original RESM method. The medium risk class method performs similarly as the APD and the Root Square methods, which are the third best ones to be considered. Then the Ashtiani RESM results in a higher total cost than the previously mentioned techniques but a lower total cost than the other ones. Next, the Copy and Paste method gives a lower total cost than the APRT method which is the worst method for the low risk seeker.

As for the second case: the high risk seeker has a lower cost assigned to exceeding the project buffer but a higher cost associated with long project buffer, or poor efficiency. The most appropriate method to use for the high risk seeker is the root square method. The medium risk class method performs almost as good as the APD method. The Original RESM and the high risk class method are roughly at the same level and take the third position. The Ashtiani RESM is next to be considered as it results in a higher total cost than the previous methods. Next it is the Cut and Paste techniques. Finally the APRT method is by far the worst one to use for a high risk seeker as it results in a much higher total cost.

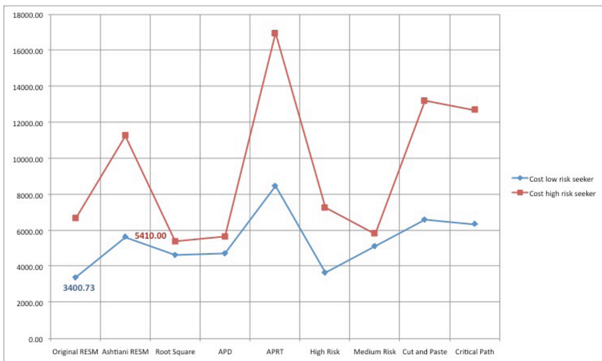

Fig. 14. Penalties overview. Modified buffer sizing techniques. Source: own elaboration

7.2. Cut and Paste 50% Goldratt

The Cut and Paste Method can be considered as a very safe and reliable buffer positioning and sizing method. Along with APRT and the Ashtiani RESM method the large buffer sizes proposed by this method almost guarantee a zero percent chance of project delay. Consequently, this is an expensive method. Because of a similar reliability and a higher cost compared to the Ashtiani RESM method, this method should not be used for this project (Figure 15).

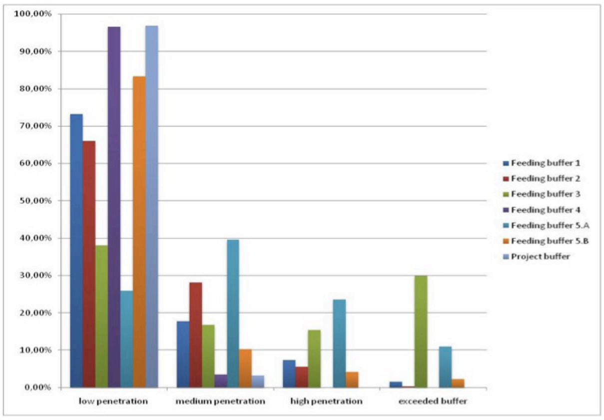

Fig. 15. Buffer penetration. Modified Cut and Paste Method. Source: own elaboration

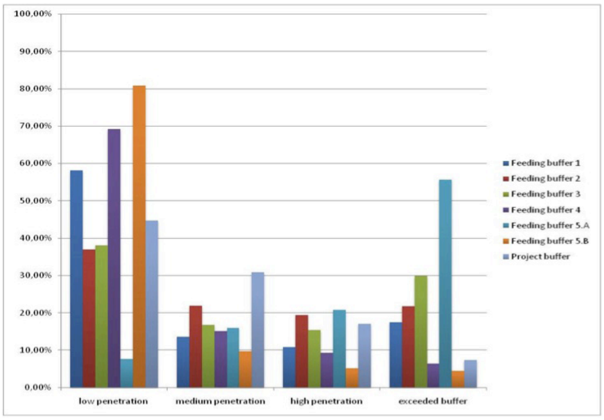

Fig. 16. Buffer penetration. Modified Medium Risk Class Method. Source: own elaboration

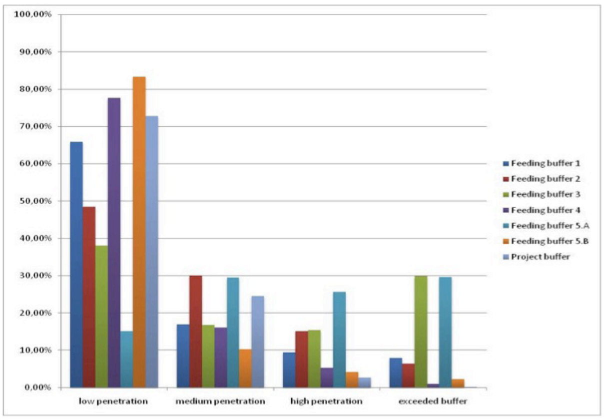

Fig. 17. Buffer penetration. Modified High Risk Class Method. Source: own elaboration

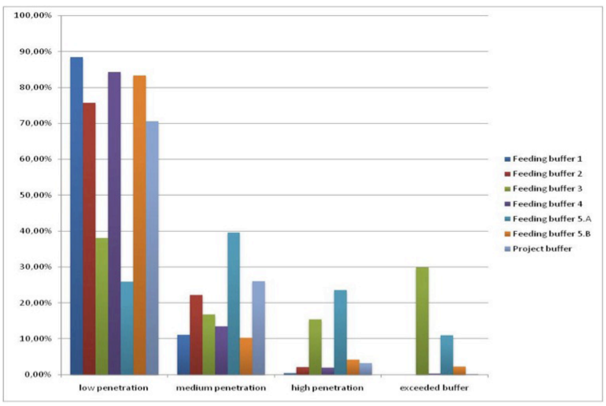

Fig. 18. Buffer penetration. Modified Original RESM. Source: own elaboration

7.3. Risk class Assessment Method

A first remark about the risk class method to be made is that the determination of buffer sizes requires some personal interpretation from the user since there are no clear guidelines on what ranges of the relative dispersion should fall within which risk class. This decision is completely up to the personal judgment of the user which makes the method a bit subjective.

The final results of the simulation show that with the medium risk method the project buffer is exceeded in 7.35% of the cases, whereas the high risk project buffer is only exceeded in 0.05% of the time. This means the high risk method gives us a much higher guarantee that the project is finished before the planned deadline, which of course is a logical consequence of the fact that the high risk method assigns much larger buffers than the medium risk method. As for efficiency, the medium risk method gives a total project buffer of 4.36 weeks which is among the smallest buffers of all the considered techniques. The project buffer length is comparable to the lengths to the buffer in the APD, 4.426 weeks, and the Root square, 4.12 weeks, methods. However, the medium risk method results in a slightly higher risk: with the APD method the project buffer is exceeded in only 6.30% of the cases and 6.45% with the Root Square method. In the case of the high risk method the total project buffer amounts up to 7.27 weeks, which is comparable to the project buffer of the Original RESM of 6.641 weeks. However, the high risk method results in less risk as the project buffer is only exceeded in 0.05% of the cases, whereas the Original RESM project buffer is exceeded in 0.20% of the cases (Figures 17 and 18).

7.4. Original RESM

Within the category of reliable, safe methods, this is one of the best methods to apply for this project. When using the modified version, it is even the best low risk method. With acceptable buffer sizes it guarantees on time delivery in 99.8% of the cases (Figure 18).

7.5. Ashtiani RESM

This method can be considered as very safe regarding the possibility of exceeding buffers. If reliability is of major importance, then this method is recommended (Figure 19).

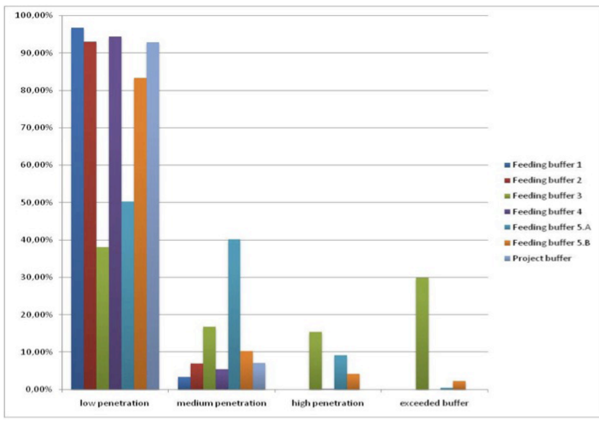

Fig. 19. Buffer penetration. Modified Ashtiani RESM Method. Source: own elaboration

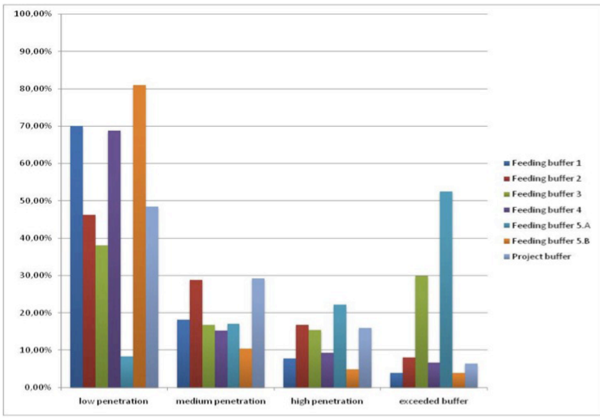

Fig. 20. Buffer penetration. Modified RSQ Method. Source: own elaboration

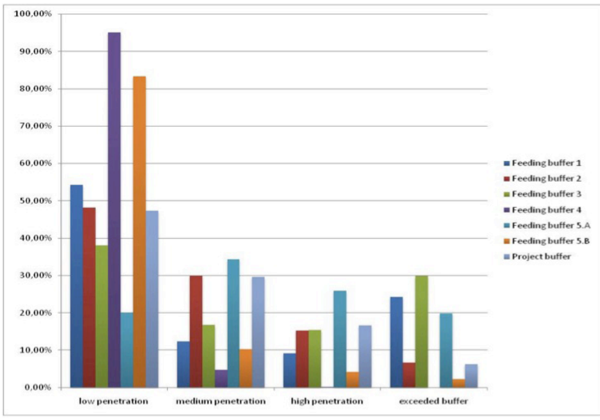

Fig. 21. Buffer penetration. Modified APD Method. Source: own elaboration

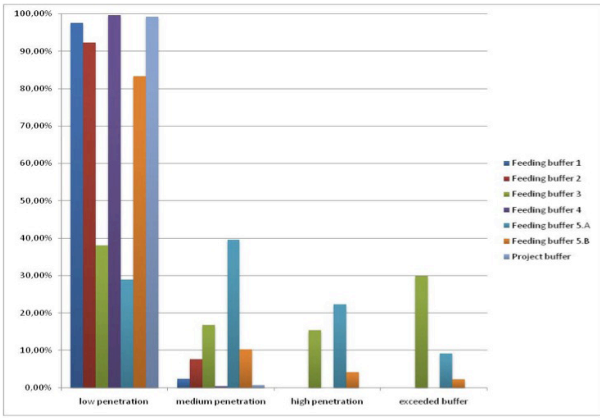

Fig. 22. Buffer penetration. Modified APRT Method. Source: own elaboration

7.6. RSQ Method

This method is much more risky than the previous ones. With its smaller buffers, project deadline will not be met in 6.45% of the cases. Although this may seem rather much, if the project manager was a high risk seeker, this would be the best method to use for this project (Figures 14 and 20).

7.7. APD Method

Adaptive Procedure with Density is a method with rather small buffer sizes. Due to this fact, while using this method it is more likely to exceed the buffer. In the considered case the project buffer will be exceeded in 6.30% of times, which is a rather high percentage. In terms of a low risk seeker this is an average method compared with the others. On the other hand in terms of "high risk seeker" this method has lower costs compared to the others (Figure 21).

7.8. APRT Method

Adaptive Procedure with Resource Tightness is for both a low risk seeker as for a high risk seeker an expensive method due to the enormous buffer sizes. On the other hand, while having such big buffers it is rather an exception to exceed the project deadline (Figure 22).

8. Conclusions

The conclusions will be divided in three parts. The first part will concern the modifications of the original methods, based on [9], for the project in question, and the second part will concern the final choice of the buffer sizing method also for the project in question. The third part will be general conclusions concerning the project time management in any project and further research.

8.1. Modification conclusion

While comparing both the original and modified buffer sizing and positioning, it becomes obvious that the modified buffer sizing and positioning delivers dominant results over the original buffer sizing and positioning. The modified approaches give both shorter expected project durations and exceed in fewer cases the project buffer.

The explanation for this dominance is dual. First, by limiting the size of the feeding buffers by the size of the total slack available and by adding the remaining part of the feeding buffer to the project buffer, the project buffers enlarge. A larger project buffer results in exceeding the project deadline less often. Secondly, by splitting up the feeding buffer 5 (the buffer for the feeding chain with tasks 7, 12 and 13), the proportion by which buffer 5.B (modified) exceeds the total available slack (1 week) is less than buffer 5 (original). This

Table 7. Penalties overview. Modified buffer sizing techniques.(I, I.a) – % of times over PB; II – extra time due to (1) PB and (2) buffer vs. slack; (II.a) – extra time due to PB

Technique name	Original		Modified	
	I	II	I.a	II.a
Original RESM	9.95%	7.90	0.20%	6.64
Ashtiani RESM	1.10%	15.07	0,00%	11.29
Root Square	11.85%	4.60	6.45%	4,12
APD	23.20%	5.50	6.30%	4.43
APRT	0.00%	20.62	0.00%	16.97
High Risk	0.80%	8.20	0.05%	7.27
Medium Risk	11.80%	4.80	7.35%	4.36
Cut and Paste	0.00%	14.50	0.00%	13.21

Source: own elaboration

reduces the critical chain and the total expected project duration as a consequence. This is shown in Table 7.

8.2. Selection of the Buffer Sizing Method for the Project in Question

Having processed all the data, it is now possible to draw a final conclusion about which buffer location and sizing technique should be proposed for the project in question. Since it is shown that the modified buffer positioning is better in all the techniques concerning the project length as well as the project risk, the authors opt to make their propositions based only on the modified schedules.

Which technique should be selected depends on how risk-averse the project manager is. In this particular project (Table 7), if the project manager is a low risk seeker, it is suggested to use the buffer sizing technique "Original RESM" which gives a total project length of 28.64 weeks (= CC (22) + PB (6.64)) and it exceeds the project buffer 0.20% of times. In the other case (project manager – a high risk seeker), it is suggested to use the buffer sizing technique "Root square" or Sum of Squares (SSQ) which gives a total project length of 26.12 weeks (= CC(22) + PB(4.12)) and it exceeds the project buffer 6.45% of the times given the information. The project manager of this particular project is working for the government, therefore he is probably risk averse, thus it is suggested to use the "Original RESM" technique. These results are confirmed by the penalties in Table 8.

Table 8. Penalties overview. Modified buffer sizing techniques

	Penalty low risk seeker	Penalty high risk seeker
Original RESM	3400,73	6681,45
Ashtiani RESM	5642,82	11285,64
Root Square	4640,00	5410,00
APD	4733,11	5686,21
APRT	8485,66	16971,32
High Risk	3656,12	7282,25
Medium Risk	5120,00	5830,00
Cut and Paste	6605,73	13211,45

Source: own elaboration

8.3. General conclusions

The paper is a case study, which shows clearly that an efficient application of the critical chain method is possible only if it is preceded by a careful study of how the buffers should be located and sized in the case in question. The authors show that there are several buffer sizing and location methods which have been proposed, but no general rules are known as to the question when which method should be chosen. The authors formulate a hypothesis that no general rules are possible and that the only way to find out how the buffers should be sized and located is simulation. A fairly easy simulation approach is proposed, which requires generally only accessible software.

However, further research is recommended to find out if the proposed hypothesis is true. The question may be asked if there can be identified some project types for which unequivocal recommendation might me formulated as to the location and size of buffers in the critical chain method application.

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Appendix

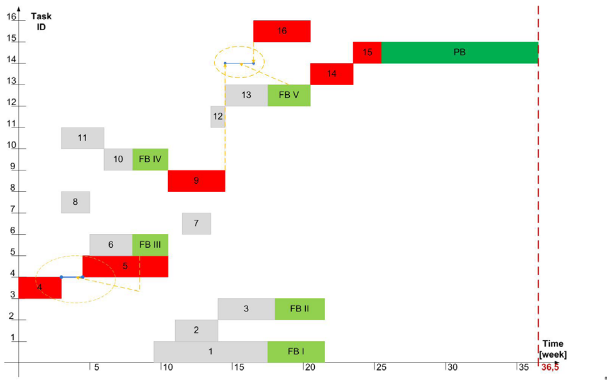

Fig. 23. Copy Paste Method

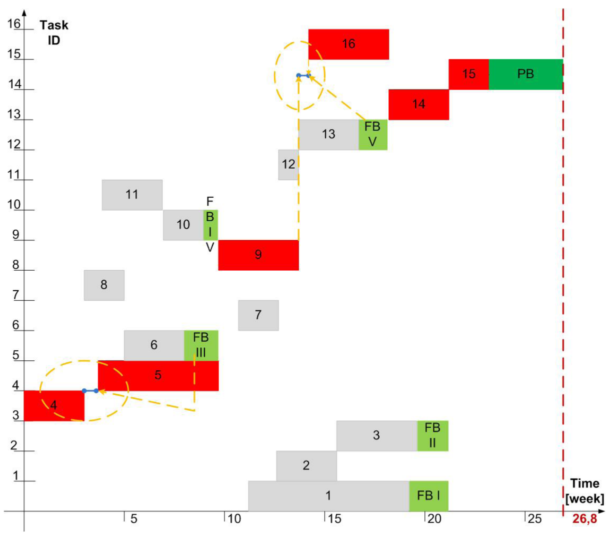

Fig. 24. Risk Classes – Medium Safety Method

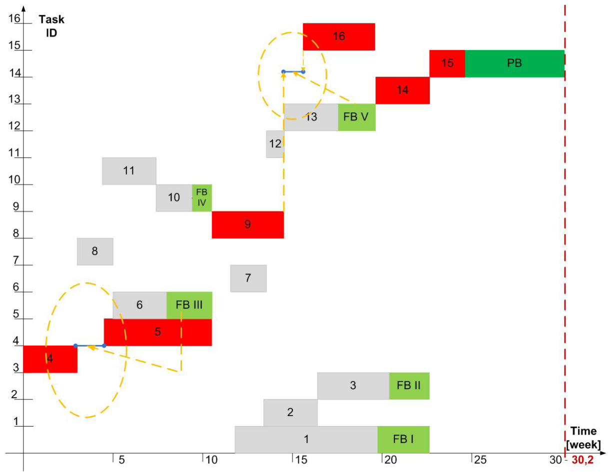

Fig. 25. Risk Classes – High Safety Method

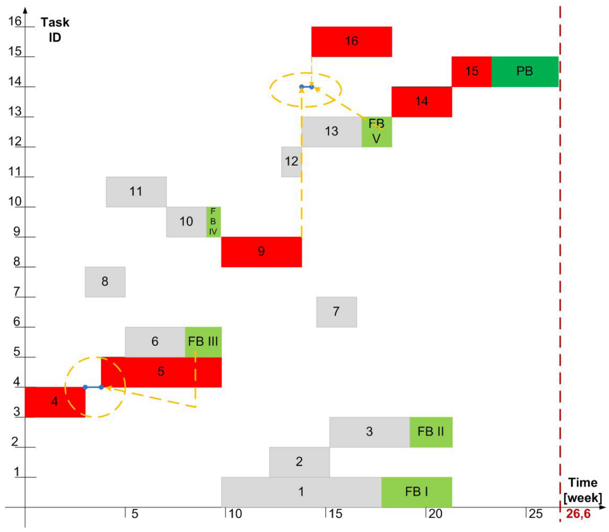

Fig. 26. Sum of Squares Method

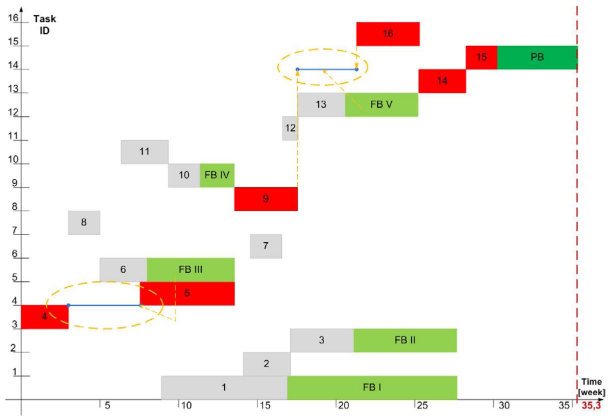

Fig. 27. Ashtiani RESM Method

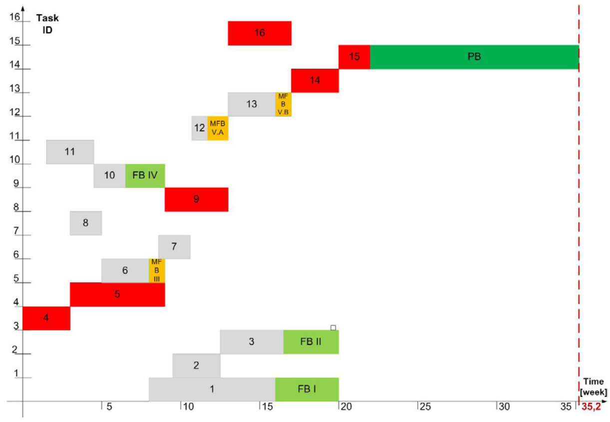

Fig. 28. Modified Copy Paste Method

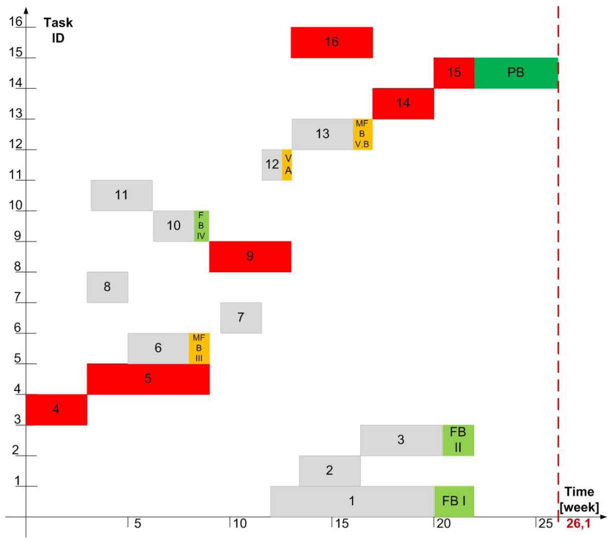

Fig. 29. Modified Risk Classes – Medium Safety Method

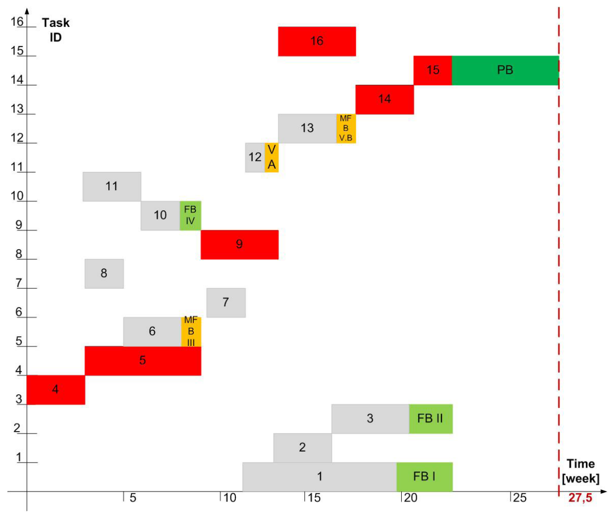

Fig. 30. Modified Risk Classes – High Safety Method

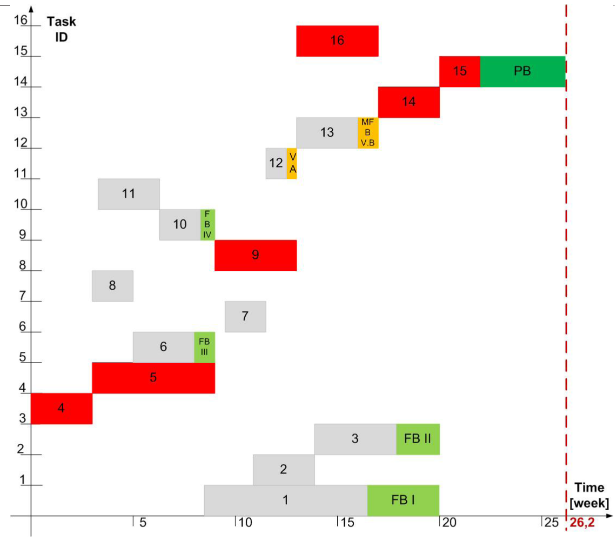

Fig. 31. Modified Sum of Squares Method

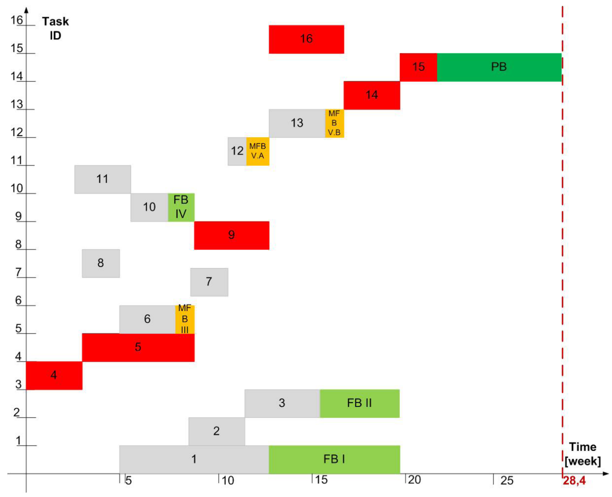

Fig. 32. Modified RESM Method

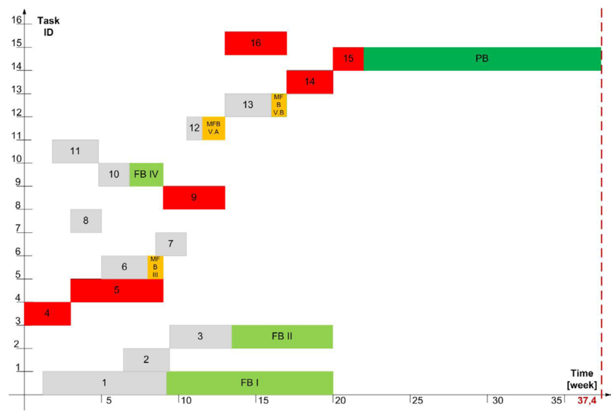

Fig. 33. Modified Ashtiani RESM Method