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A MULTI-CRITERIA APPROACH TO OPTIMAL BUFFER SIZING IN THE CRITICAL CHAIN METHOD

Abstract:

The paper presents the methodology for determining the most favorable method for buffer sizing in the Critical Chain Method (CCM), which is based on multi-criteria decision-making methods. The proposed methodology enables a complete and systematic solution to this problem, whose end result is a proposal for a buffer sizing method in accordance with the adopted criteria and realistic limitations. The developed methodology is based on the PROMETHEE method, and its verification was carried out on a case study of the construction of a residential building. The results showed that the CCM-RSEM method is the most effective for planning and project management in construction.

Keywords: critical chain, CCM, buffers, multi-criteria decision-making, PROMETHEE

ВИШЕКРИТЕРИЈСКИ ПРИСТУП ОДРЕЂИВАЊУ ОПТИМАЛНЕ ВЕЛИЧИНЕ БАФЕРА У МЕТОДИ КРИТИЧНОГ ЛАНЦА

Сажетак:

У раду је приказана методологија одређивања најповољније методе за димензионисање бафера у методи критичног ланца CCM, која се темељи на методама вишекритеријског одлучивања. Предложена методологија омогућава цјеловито и системско рјешавање овог проблема, чији крајњи резултат је приједлог методе за димензионисање бафера у складу с усвојеним критеријима и реалним ограничењима. Развијена методологија је базирана на PROMETHEE методи, а њена верификација проведена је на студији случаја изградње стамбене зграде. Резултати су показали да је метода CCM-RSEM најефикаснија за планирање и управљање пројектима у грађевинарству.

Кључне ријечи: критични ланац, CCM, бафери, вишекритеријумско одлучивање, Promethee.

1. INTRODUCTION

Planning is the primary phase of every management process, including project management. It involves defining the objectives as well as the methods for achieving those objectives. Planning reduces risks because it enables the early identification of errors, cost control, and quality improvement. The methods used for project planning may vary, but the most commonly used and widely applied are network planning methods and Gantt charts. The most well-known network planning methods are the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT). Since 1997, a new planning technique known as the Critical Chain Method (CCM) has been used. This method has become increasingly popular and represents a competitive alternative to the traditional Critical Path Method (CPM).

This paper presents the methodology of project planning and management using the Critical Chain Method (CCM). Different variants of CCM are analyzed, and the obtained results are compared. Finally, the most suitable CCM variant is determined using the multi-criteria decision-making method PROMETHEE–GAIA.

2. LITERATURE REVIEW

Project planning methods represent a set of techniques and tools used to define activities, determine their sequence, estimate their duration, and allocate resources, with the aim of ensuring the efficient implementation of a project within the specified deadlines and budget. Traditional project planning methods, CPM and PERT, have been widely criticized due to the fact that they neglect the influence of human behavior on project implementation [1], [2]. Research results indicate that theoretical project planning focuses on activity sequencing, resource allocation, and optimization, while planning in practice is more focused on social and organizational processes [3], [4]. Research conducted in the Netherlands and Belgium has shown that project planning software is used more for communication and monitoring project implementation than for optimizing the project plan [5].

The problems that arise in project planning and management using the CPM/PERT methods can be overcome by a more recent project management approach known as the Critical Chain Method (CCM). The CCM was developed by Eliyahu M. Goldratt and was first introduced in 1997 in the novel Critical Chain, in which he criticizes static deterministic planning [6]. CCM is based on the Theory of Constraints (TOC). This method represents a completely new way of thinking, where the emphasis is placed on aggressively shortening activity durations, managing project buffers instead of individual activity time reserves, and focusing on resources completing activities on time. The main idea of the method's author is to identify the critical chain of activities in a manner similar to the critical path, but taking into account both the logical relationships between activities (as in the CPM method) and resource constraints [7]. The project plan is protected against disruptions using different types of buffers strategically placed at key points [4], [8], [9].

In the Critical Path Method, activities are protected against uncertainty through time reserves, which allow the activities, and consequently the project, to be completed on time. The Critical Chain Method uses a different approach to protect against uncertainty. The goal of CCM is to safeguard the project from delays rather than individual activities. In CCM, activities do not have individual time reserves; the safety and protection against uncertainty removed from the activities are aggregated and inserted at the end of each chain, i.e., path in the network diagram, in the form of buffers [4].

The CCM method employs three types of buffers to manage uncertainty: the Project Buffer (PB), placed between the last activity of the critical chain and the project completion date to protect the critical chain from delays; the Feeding Buffer (FB), inserted after the last activity of a non-critical chain to shield the critical chain from delays originating in the non-critical chain; and the Resource Buffer (RB), allocated to critical chain activities to ensure that the necessary resources are available when required. The total project duration is equal to the sum of the critical chain duration and the project buffer.

3. RESEARCH METHODOLOGY

The paper presents a comparison between the CCM and traditional CPM methods, based on a case study of a residential building construction project. The data were obtained from a real-world project, with MS Project software employed for project planning. The methodology for comparing CCM and CPM is illustrated in Figure 1.

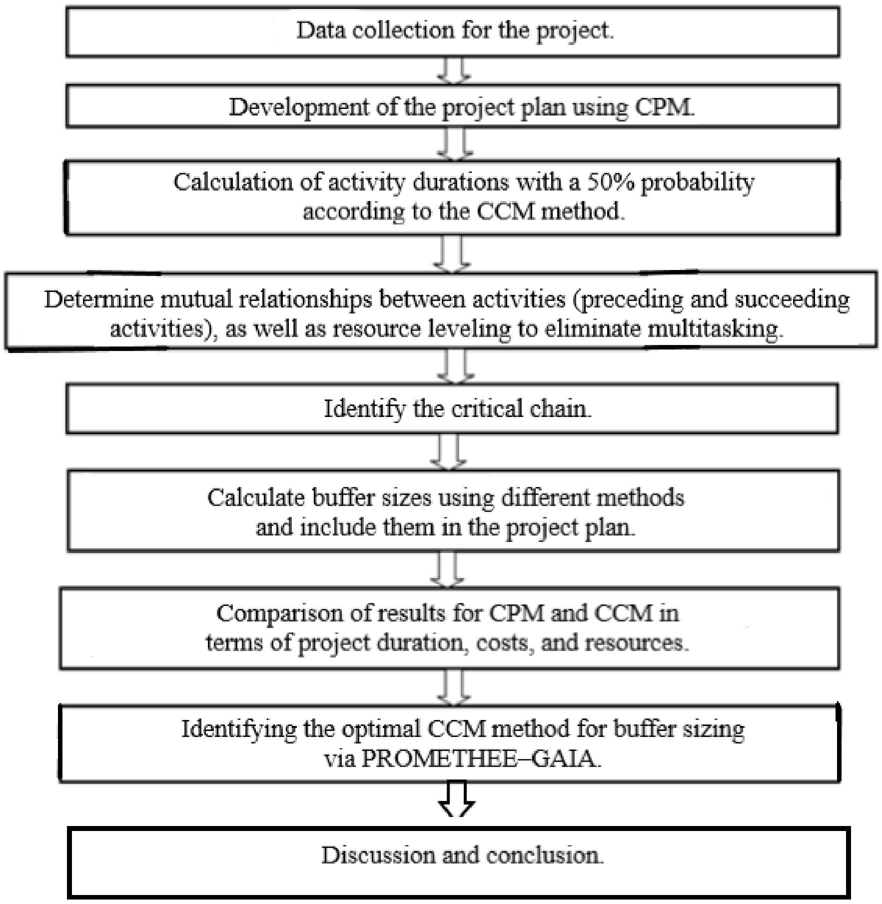

Figure 1. Research methodology (drawing by author).

CCM buffers are sized using four different methods:

- Cut and Paste Method - C&PM
- Root Square Error Method - RSEM
- Adaptive Procedure with Resource Tightness Method - APRT
- Adaptive Procedure with Density Method - APD

C&PM is the first proposed method for determining buffer sizes, introduced by Goldratt in his book *Critical Chain* (1997). It is the simplest of all buffer sizing methods. Activities are assigned realistic durations with a 50% probability, instead of the pessimistic durations with a 90% probability used in the CPM method. According to the C&PM method, the project buffer (PB) is equal to half the duration of the critical chain, while the feeding buffer (FB) is equal to half the duration of the feeding chain, i.e., the non-critical chain [3], [6], [9]. Although this method allows buffer sizes to be calculated very easily, it has limitations, such as neglecting the uncertainties present in activities and generating large buffers for long-duration activities.

The RSEM (Root Square Error Method) determines the buffer size as the square root of the sum of the squares of the differences between the original (90%) and aggressive (50%) durations for each activity along the chain. It performs somewhat better than the C&PM method, but it is associated with the limitation that the probability of the duration exceeds 90%, which likely reduces the project buffer (PB) size more than necessary for critical chains, while resulting in larger feeding buffers (FB). This is the main drawback of the method. An undersized project buffer and oversized feeding buffers can lead to project failure [4], [9].

The APRT method determines the buffer size as the product of a scaling factor ‘K’, based on the resource compression rate, and the standard deviation of the activities followed by the buffer [10].

$$Buffer = \mathrm{K} \times \sigma \quad (1)$$

Where K = (total resources used/ total resources available). In this calculation, the central limit theorem is applied to the standard deviation of the chain, which emphasizes that the mean duration of the chain equals the sum of the mean durations of the activities that constitute the chain. Similarly, the variance of the chain is equal to the sum of the variances of the activities forming the chain. The square root of the variance then gives the value of the standard deviation.

The APD method uses the concept that project delays are influenced by the complexity of the project network plan, i.e., a higher number of predecessor links (activities) among activities. In other words, the interdependence between activities is directly proportional to the delays occurring in the project. The more complex the project network plan—meaning activities have a larger number of preceding activities—the greater the likelihood of project delays. The APD method determines the buffer size as the product of the project network complexity factor 'H' and the standard deviation of the activities followed by the buffer [10].

$$Buffer = \mathrm{H} \times \sigma \tag{2}$$

Where H = 1 + (total number of preceding activities in the considered chain /total number of activities in the considered chain).

After calculating the buffers using these different methods, the results were compared, and a conclusion was drawn regarding the most suitable method for application in construction projects, supported by the PROMETHEE–GAIA multi-criteria decision-making approach.

The PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) method is a recent approach in the field of multi-criteria decision analysis. It comprises a family of methods, commonly referred to as PROMETHEE I, II, III, IV, V, and VI.

The PROMETHEE–GAIA method is a multi-criteria decision-making (MCDM) approach that integrates numerical ranking with graphical visualization.

In the PROMETHEE method, a decision matrix R is used, which is also commonly referred to as the payoff, rating, or performance matrix. Each row of the matrix corresponds to one alternative, and each column to one criterion; element r_{ij} represents the rating (performance) of the alternative a_j in relation to the criterion C_i. For I criteria $(C_1, C_2, ..., C_I)$ and J alternative $(a_1, a_2, ..., a_J)$ the matrix R has the form (1), and the values $(w_1, w_2, ..., w_I)$ are entered above the matrix represent the weight values of the criteria defined by the decision maker, or otherwise determined. The sum of these weight values is 1 [11].

$$R = \begin{array}{c} \\ \\ a_1 \\ a_2 \\ \vdots \\ \vdots \\ a_J \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_I \\ w_1 & w_2 & \cdots & w_I \end{array} \\ \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1I} \\ r_{21} & r_{22} & \cdots & r_{2I} \\ \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ r_{J1} & r_{J2} & \cdots & r_{JI} \end{bmatrix} \end{array} \tag{3}$$

In order to make a good decision, it is necessary to specify alternatives by defining appropriate criteria. It is also necessary to define the weighting coefficients for each criterion, i.e. the importance of each criterion in relation to the others. Weights are usually numbers that are subjectively chosen. In addition, for each criterion, it is determined whether it is necessary to choose an alternative so that the criterion is minimal or maximum, or what is the nature of that criterion. Since each criterion is measured in a specific way, the preference function $Pi\ (a_j, a_m)$ is defined for each, which defines the intensity of the difference between the alternatives a_j and a_m [12].

The alternatives considered in this study are methods for buffer dimensioning based on the CCM method, namely the C&PM, RSEM, APD, and APRT methods. The criteria for evaluating the alternatives are project duration, project buffer duration, and feeding buffers duration (PD, PB, FB1, FB2, FB3, FB4, FB5). The weighting coefficients are different for each criterion and for project duration is 0.50, for project buffer is 0,25, and for each feeding buffer is 0.05. This is shown in Table 2.

The evaluation of alternatives consists in determining the index of multi-criteria preference $\Pi(a_j, a_m)$. The ranking of alternatives is done according to the decreasing values of the preference index. $\Pi(a_j, a_m)$ shows how much the alternative a_j is better (more favorable) than the alternative a_m, considering all the criteria. The value of the preference index ranges from 0 to 1. If $\Pi(a_j, a_m) = 0$, then alternative a_j is not better (no difference) than alternative a_m by all criteria. If $\Pi(a_j, a_m) = 1$, then the alternative a_j is much better (complete dominance) than the alternative a_m by all criteria [13].

Ranking of alternatives is done based on preference flows. The positive flow of preference $\Phi^+_j\ (a_j)$ shows that alternative a_j is better (more favorable) compared to other alternatives. The best alternative has the highest value of the positive flow of preference Φ^{+}. The negative flow of preference Φ^{-}_{j} (a_j) shows that all other alternatives are better (more favorable) compared to alternative aj. The best alternative has the lowest value of the negative flow of preference Φ^{-}. The net flow of preference Φ represents the difference between the positive and negative flow of preference and the higher its value, the better (more favorable) the alternative [12,13,14].

GAIA (Geometrical Analysis for Interactive Aid) complements PROMETHEE by providing a visual representation of the decision problem. It projects alternatives and criteria into a geometric space, allowing decision-makers to:

- observe relationships between criteria,
- identify conflicts or similarities among them,
- analyze the position of alternatives,
- and determine the direction of the best compromise solution (decision axis) [13,14].

4. RESEARCH RESULTS

Figure 2 illustrates the input data utilized for developing project plans using the CCM and CPM methods.

No.	Activity	CPM duration 90%	CCM duration 50%	Standard deviation σ
1	A	4	2	0.5
2.	B	5	2.5	0.625
3.	C	10	5	1.25
4.	D	3	1.5	0.375
5.	E	10	5	1.25
6.	F	13	6.5	1.625
7.	G	8	4	1
8.	H	15	7.5	1.875
9.	I	13	6.5	1.625
10.	J	7	3.5	0.875
11.	K	8	4	1
12.	L	15	7.5	1.875
13.	M	8	4	1
14.	N	3	1.5	0.375
15.	O	8	4	1
16.	P	4	2	0.5
17.	Q	3	1.5	0.375
18.	R	22	11	2.75
19.	S	10	5	1.25

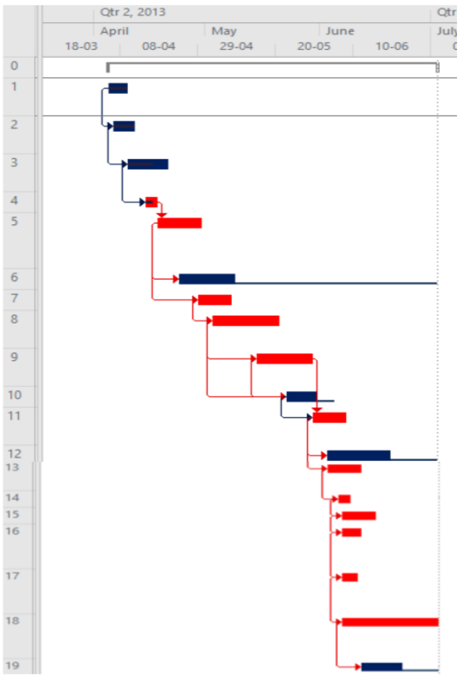

Figure 2. Input data for the residential building project and the project schedule developed using the CPM method (drawing by author).

The results obtained for the PB and FB buffers, along with the project durations for all methods, are summarized in Table 1.

Table 1. Values of buffers and the project duration

Buffer	CPM	CCM			
		C&PM	RSEM	APRT	APD
	days	days	days	days	days
PB		26.25	17.87	71.85	19.89
FB1		4.75	5.94	1.25	2.09
FB2		3.25	6.5	1.625	1.625
FB3		1.75	3.5	0.875	0.875
FB4		3.75	7.5	1.875	1.875
FB5		2.5	5	1.25	1.25
Total project duration - PD	90	78.75	70.37	124.35	72.39

A set of 7 criterion functions has been adopted for multi-criteria optimization for buffer sizing method in CCM:

1. The total project duration (PD)
2. The duration of Project Buffer (PB)
3. The duration of FB1
4. The duration of FB2
5. The duration of FB3
6. The duration of FB4
7. The duration of FB5

The values of the criterion functions are shown in Table 2. For each criterion function, a simple preference function is adopted, i.e. Type I ("simple criterion").

Table 2. Criterion functions

		Criterion functions						
Name		f_1 - PD	f_2 – PB	f_3 – FB1	f_4 – FB2	f_5 – FB3	f_6 – FB4	f_7 – FB5
Unit		days	days	days	days	days	days	days
Ekst.		min	min	min	min	min	min	min
w_i		0.50	0.25	0.05	0.05	0.05	0.05	0.05
Alternatives	C&PM	78.50	26.25	4.75	3.25	1.75	3.75	2.50
	RSEM	70.37	17.87	5.94	6.50	3.50	7.50	5.0
	APRT	124.35	71.85	1.25	1.625	0.875	1.875	1.25
	APD	72.39	19.89	2.09	1.625	0.875	1.875	1.25

The ranking of alternatives is determined on the basis of the positive preference flow (Φ^+), the negative preference flow (Φ^-), and the net preference flow (Φ). The most favorable alternative is characterized by the highest value of the positive preference flow (Φ^+), the lowest value of the negative preference flow (Φ^-), and consequently the highest value of the net preference flow (Φ) [15]. As shown in Figure 3, the RSEM method represents the optimal solution.

PROMETHEE Flow Table

Rank		Phi	Phi+	Phi-
1	RSEM	0,500	0,750	0,250
2	APD	0,400	0,666	0,266
3	Cut and Paste	-0,33	0,333	0,666
4	APRT	-0,56	0,183	0,750

Figure 3. PROMETHEE Flow Table (drawing by author).

The Visual Promethee software graphically displays the results of ranking alternatives [16].

Figure 4 shows the ranking of alternatives by the PROMETHEE 1 method. This method performs a partial evaluation of the positive negative flows (deviations) of the preference functions Φ^+ and Φ^-, on a set of criteria for each alternative. PROMETHEE I is used to identify dominance relationships among alternatives; however, it may lead to incomparability in cases where an alternative exhibits a higher positive preference flow (Φ^+) but simultaneously a higher negative preference flow (Φ^-) compared to another alternative. As a result, not all alternatives need to be ranked one after the other. In this case, all alternatives are ranked one after the other, as we can see in the Figure 4 and Figure 5.

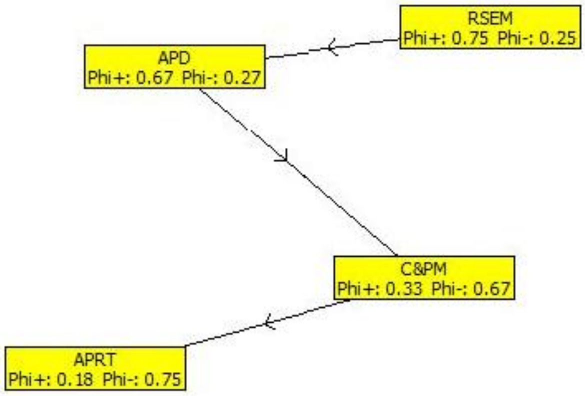

Figure 4. PROMETHEE Network (drawing by author).

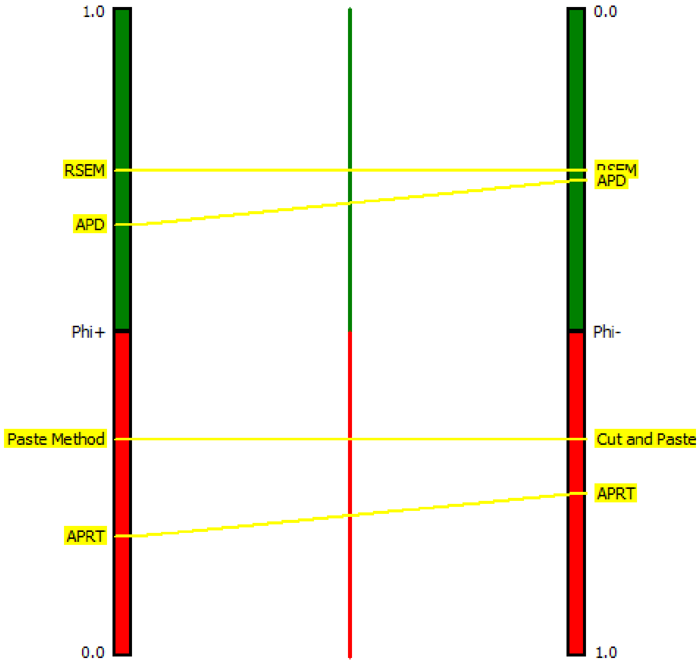

Figure 5. PROMETHEE I Partial Ranking (drawing by author).

Figure 6 shows the ranking of the alternative according to the PROMETHEE 2 method. This method realizes a complete evaluation of the alternatives, using the net flow (deviation) of the preference function Φ. All alternatives are ranked one after the other, from the best to the worst. PROMETHEE II eliminates incomparability by aggregating positive and negative preference flows into a single net preference value, making it suitable when a clear and complete ranking of alternatives is required.

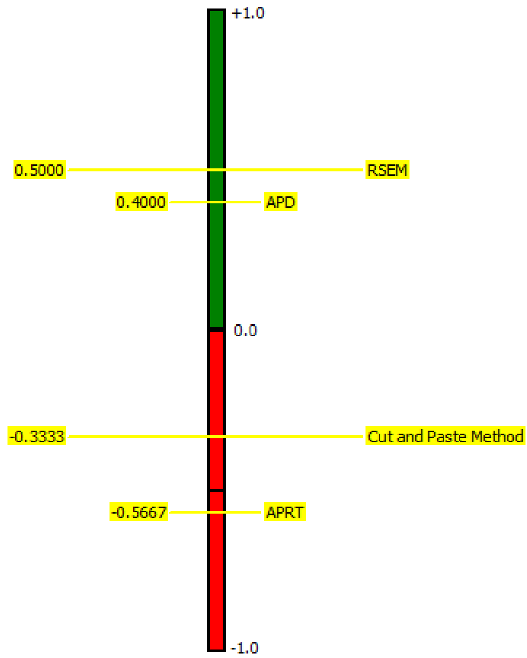

Figure 6. PROMETHEE II Complete Ranking (drawing by author).

In PROMETHEE visualisation tools, unicriterion flows allow decision-makers to analyze the strengths and weaknesses of alternatives for each criterion individually, facilitating a deeper understanding of the overall ranking results [17,18].

According to Figure 7, the RSEM method has the highest net unicriterion flow (Φ) for criteria 1 and 2. This indicates that RSEM is the best choice for these criteria (project duration PD and project buffer PB), whereas for the other criteria it is not the best option, as its net unicriterion flow (Φ) is negative.

Observing criteria 3, 4, 5, 6, and 7 (FB1, FB2, FB3, FB4, FB5), the highest net unicriterion flow (Φ) is achieved by the APRT method, which indicates that it is the best choice for these criteria.

The APD method is the only one with positive net unicriterion flow (Φ) values across all criteria, suggesting that it may represent the best compromise solution when all criteria are considered together.

Φ Preference Flows

	Total Project Duration	PB	FB1	FBr 2	FB 3	FB 4	FB 5
Cut and Paste Method	-0.3333	-0,3333	-0,3333	-0,3333	-0.3333	-0,3333	-0,3333
RSEM	1.0000	1,0000	-1.0000	-1,0000	-1.0000	-1,0000	-1.0000
APRT	-1.0000	-1,0000	1.0000	0.6667	0,6667	0,6667	0,6667
APD	0,3333	0.3333	0,3333	0.6667	0.6667	0.6667	0,6667

Figure 7. Preference Flows – Unicriterion (drawing by author).

The net multicriteria flow is used for the final ranking in the PROMETHEE I or PROMETHEE II method [17,19]. The best alternative is the one with the highest value of the net multicriteria flow (Φ).

Figure 8 presents the multicriteria preference flows for all four variants. The highest positive value of the net multicriteria preference flow is obtained by the RSEM method, indicating that RSEM represents the best compromise solution considering all criteria. The APD method has a slightly lower value of the net multicriteria preference flow, which means that it represents the second-best compromise solution.

Φ Preference Flows

	Phi+	Phi-	Phi
Cut and Paste Method	0,3333	0.6667	-0,3333
RSEM	0,7500	0.2500	0.5000
APRT	0,1833	0.7500	-0.5667
APD	0.6667	0.2667	0,4000

Figure 8. Preference Flows – Multicriteria (drawing by author).

The ranking of alternatives obtained through the PROMETHEE I and PROMETHEE II methods is based on the predefined criteria weights. The software feature referred to as 'Walking Weights' allows for dynamic adjustment of these weights and provides a graphical representation of the resulting changes in the PROMETHEE II ranking, as presented in Figure 9. Walking Weights is a sensitivity analysis technique used in multicriteria decision-making methods (including PROMETHEE) to examine how changes in criteria weights affect the ranking of alternatives [20].

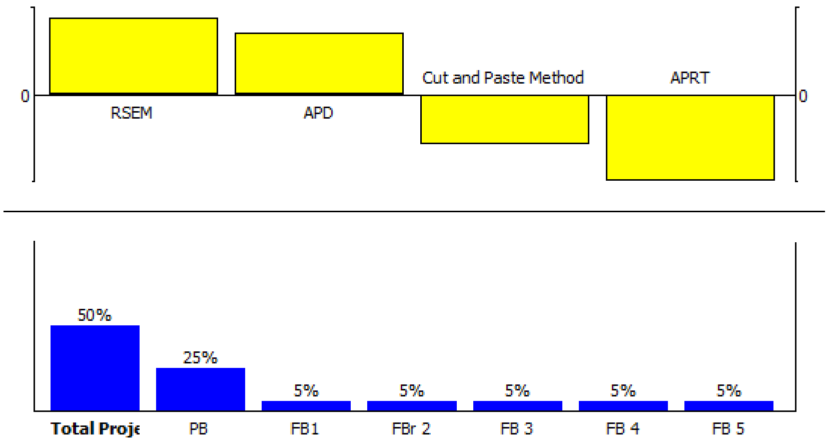

Figure 9. Walking Weights and ranking methods from best to worst (drawing by author).

Information about the problem of multi-criteria decision-making, which has *i*-criteria, can be displayed in *i*-dimensional space.

A GAIA Visual Analysis is a plan obtained by projecting all information into two-dimensional space. In the GAIA Visual Analysis, alternatives are represented by triangles, and criteria by axes. The conflicting characteristics of the criterion are clearly shown in the diagram, the conflicting criterion is oriented in opposite directions (directions), while the criterion that has a similar preference (advantage) is oriented in the same direction. It is also possible to clearly classify the qualities of alternatives according to the given criteria [14,16]. Figure 10 shows that the RSEM method performs particularly well with respect to the first and second criteria (Project Duration – PD and Project Buffer – PB), while the APD method demonstrates better performance in relation to the third and seventh criteria (FB1 and FB5).

According to the position of the vector π in the GAIA plan (Figure 10), it can be concluded that the best compromise solution is the RSEM method, because vector π shows the direction of the compromise solution. The same was obtained by the methods of PROMETHEE 1 and PROMETHEE 2.

The ranking list of alternatives obtained by both PROMETHEE 1 and PROMETHEE 2 methods is the same and looks like this: RSEM, APD, Cut and Paste Method (C&PM), APRT.

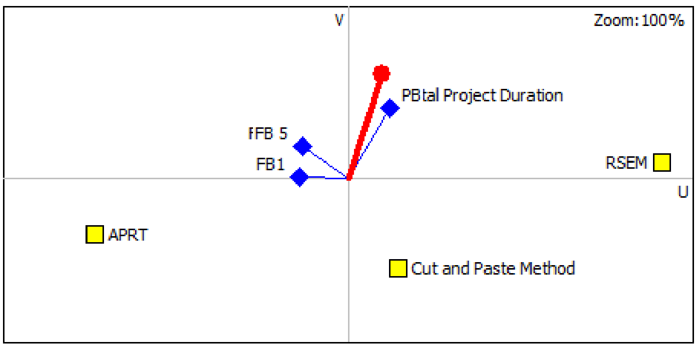

Figure 10. GAIA Plane (drawing by author).

5. DISCUSSION AND CONCLUSION

The comparison of results indicates that the CCM method outperforms the CPM method in terms of project duration, with projects completed in a shorter time using CCM.

However, the application of the CCM method may also result in different buffer sizes and varying total project durations, which directly depend on the chosen method for sizing the project buffers.

The shortest project durations are achieved using the RSEM and APD methods, while the APRT method results in the longest project duration. The ranking of methods based on project duration is as follows: RSEM < APD < C&PM < APRT. Comparing the obtained project buffer (PB) values, the smallest PB is obtained with the RSEM method, whereas the largest PB is produced by the APRT method. The ranking of methods according to PB size is: RSEM < APD < C&PM < APRT. Regarding the feeding buffer (FB) values, the smallest FB is obtained using the APRT and APD methods, while the largest FB is given by the RSEM method. The ranking of methods based on FB size is: APRT < APD < C&PM < RSEM.

From the perspective of project duration and project buffer (PB) values, the RSEM method provides slightly better (shorter) results compared to the APD method. However, the RSEM method does not account for uncertainty in the buffer calculation, whereas the APD method incorporates this factor.

By applying the PROMETHEE multi-criteria decision-making method, it was determined that the most favorable buffer sizing method is RSEM. Considering all evaluation criteria, the methods for project buffer sizing in the CCM framework were ranked. The ranking of alternatives obtained using both PROMETHEE I and PROMETHEE II methods is identical and is as follows: RSEM, APD, Cut and Paste Method (C&PM), APRT.

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