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RESEARCH ARTICLE

CRITICAL PATH METHOD with FUZZY ACTIVITY TIMES

Özlem ÇOMAKLI SÖKMEN[1*]

[1]Erzurum Technical University, Career Planning Application and Research Center, Erzurum, ozlem.sokmen@erzurum.edu.tr,
ORCID: 0000-0001-8765-0038

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ABSTRACT

The Critical Path Method (CPM) is very useful in planning and controlling complex projects when their activity times are known precisely. However, in real-life applications, the durations are foreseen in the planning phase of the project; when it is put into practice, it may vary due to various reasons such as machine breakdowns, human factors, and disruptions in material supply. Accordingly, due to the uncertainty and difficulties in estimating operating times, CPM may not be able to accurately and fully represent real projects. From this point of view, in this study, it is aimed to perform critical path analysis in a project network whose activity durations consist of triangular fuzzy numbers. In the first stage, critical path analysis and project completion time were found by using possible, optimistic and pessimistic values. Then, Yager's ranking method was used to ranking the fuzzy numbers and the project completion time and critical path were calculated with the crisp values obtained. The results were evaluated by comparing and the importance of using fuzzy numbers instead of crisp numbers in the CPM method was revealed.

Keywords: *Critical Path Method, Fuzzy Logic, Fuzzy Number, Fuzzy Project Network, Ranking Index*

1. INTRODUCTION

In today's business world, where competition is increasing, the completion of projects in the least time and with the least cost is an important factor that increases the success of enterprises in project management activities. In this competitive environment, the most effective planning of the projects and their completion within the stipulated time without delay provide a great advantage in terms of cost, time and customer satisfaction. Therefore, the need and interest in project management methods are increasing in order to ensure calendar success and maintain permanence in the sector. Various methods are used in project planning, which is an important step in project management. CPM is one of the most preferred methods for an effective management system. The critical path is the path from the start to the end of the project where all slack times are zero [1]. CPM, on the other hand, aims to identify critical activities on the critical path so that resources can be concentrated on critical activities in order to reduce the length of the project. In addition, bottlenecks in the project can be determined

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with CPM [2]. In short, CPM is a method that determines the completion time of the project by taking into account the priority relations between the activities. CPM is a useful tool for planning and managing complex projects in real-life applications [3]. This method is very effective in determining the project completion time and critical path when the activity times are known precisely. However, in real-life applications, project activity times can be uncertain due to various factors, and in this case, calculations made with classical CPM may not fully reflect real-life situations. In CPM, the fuzzy logic approach can be used to express uncertainty mathematically. Fuzzy logic, introduced by Zadeh [4] in 1965, allows extreme values of mathematics, unlike classical logic. It is difficult to model complex systems because classical logic requires precise values [5]. However, fuzzy logic, unlike classical logic, is a concept that allows the use of linguistic variables that deal with uncertain values. In this way, fuzzy logic provides an advantage in solving complex systems. Fuzzy logic is a control method based on fuzzy set theory that transforms real values into linguistic variables [6]. Fuzzy logic has wide application areas. Fuzzy logic is used in many areas such as Optimization, Operations Research, Statistics, Quality Control, Production Planning, and Process Control [7].

In real-life applications, it may not always be possible to precisely determine the duration of activities for projects. Activity durations in the project can be determined based on expert opinions and estimates. However, even for the same project, the estimations of different experts regarding the duration of activity may differ [8]. When the relevant literature is examined, it is seen that studies in which CPM is handled with the fuzzy logic approach are encountered. A bibliometric analysis of the studies in which CPM was handled with a fuzzy logic approach was made in the Web of Science (WoS) database. The studies in this field were reached by entering the word groups "Fuzzy Critical Path Problem* or Fuzzy Critical Path Method*" into the WoS database. Keyword network analysis was done using the VOSviewer (Version 1.6.16) package program. According to the bibliometric analysis made using the VOSviewer program, the most used keywords are shown in Figure 1.

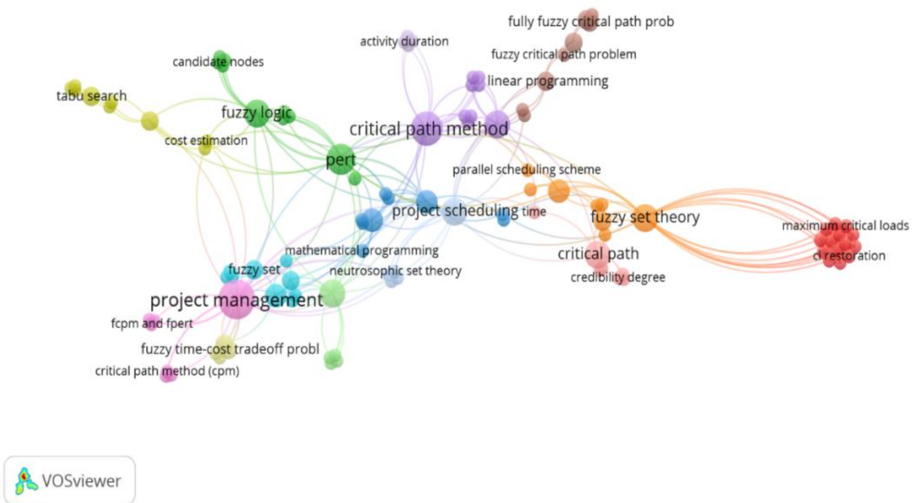

Figure 1. Keywords network analysis (VOSviewer).

As can be seen in Figure 1, among the most used keywords in studies where CPM is handled with fuzzy logic approach, "critical path method", "project scheduling", "fuzzy logic", "project management", "fuzzy set theory", "PERT" is located. In addition, it is understood that triangular fuzzy numbers and trapezoidal fuzzy numbers, which represent fuzzy activity times, are among these keywords.

Some of the studies in this area are given in this section. In some of these studies, fuzzy linear programs were used, and in some of them, activity times were represented by fuzzy numbers. The fuzzy logic approach was first applied to the scheduling problem in 1979 [9]. In [10], the authors applied a signed distance ranking method to the critical path method for activity-on-edge. This method allows the use of both positive and negative values in the ranking. In [11], the authors discussed the use of the fuzzy CPM (FCPM) method to find and improve airports' ground handling critical processes. Trapezoidal fuzzy numbers were used in the study. In [12], the author applied a linear programming formulation to calculate the lower and upper limits of the project duration in finding the critical path in a project network created using fuzzy numbers and created a membership function for the fuzzy total time. In [13], the authors proposed the expected cost model, α-cost minimization model and credibility maximization for solving fuzzy project scheduling problems. In [2], the authors discussed a project in which activity durations were expressed as trapezoidal fuzzy numbers in their study. In the study, a new analytical method and a new method for the defuzzification of fuzzy numbers are proposed. This method is applied to all float time in the project network. In [14] the authors developed a linear program and fuzzy arithmetic approach to solving the trapezoidal fuzzy action time CPM problem and proved the validity of the proposed method by comparing the methods with each other. In [15], the authors examined a project network in a fuzzy environment with activity durations normalized trapezoidal fuzzy numbers. To find the Earliest Start (ES) time and the Latest Finish (LF) time, a method is proposed to obtain the maximum and minimum of trapezoidal fuzzy numbers to be used during forward and backward transition calculations. In [8] the authors used α-cut and centroid methods to determine the critical path and completion time in a construction project with triangular fuzzy activity times and compared the results. In [16] the authors examined a fuzzy project network containing hexagonal fuzzy numbers and generalized hexagonal fuzzy numbers and obtained the fuzzy critical path by ranking method. In [17], the authors proposed a new approach in which the fuzzy numbers are ranking based on the centroid to find the critical path in a fuzzy project network where the activity times are expressed as hexagonal fuzzy numbers. In [18], the authors discussed CMP with imprecise activity time in their study. They developed a new approach to CPM based on ordered fuzzy numbers in case of uncertainty. In [19] the authors presented a new fuzzy node labeling method, taking into account the uncertainty in their work. The proposed method is quite useful for quickly identifying the critical path of fuzzy project networks. In [20] the authors propose the ranking function to solve project scheduling problems in a fuzzy environment. In the study, trapezoidal fuzzy numbers are converted to crisp values and an algorithm is presented to obtain the best result in the completion times of the fuzzy network. In[21], the authors proposed two different algorithms to find the project completion time and critical path using triangular fuzzy numbers in the activities of a construction project. Using the proposed solution algorithms, fuzzy and crisp project durations are compared. In [22] the authors used decagonal fuzzy numbers. Decagonal fuzzy numbers were converted into crisp time. In the study, the authors aimed to perform correlation and regression analysis on decagonal fuzzy numbers in comparison with the statistical mean. In [23] the authors used

FCPM and FPERT to estimate the activity completion time of a hydroelectric power project. Trapezoidal fuzzy numbers were used in the study. Project durations were obtained by using both methods and the methods were compared. In [24] the authors used neutrosophic fuzzy numbers to solve the fuzzy critical path problem. Then the mathematical model of neutrosophic CPM and a method to calculate Critical path in project network is proposed.

Based on the uncertainty in the activity durations, a project process in a enterprise operating in the production sector is discussed in this study. The situation where the duration of the activity is uncertain has been examined. Activity times were expressed with triangular fuzzy numbers. The fuzzy numbers were ranking using Yager's ranking index and the obtained results were compared with the results obtained with fuzzy values.

2. MATERIAL and METHODS

2.1. Critical Path Method

CPM is a technique for scheduling a set of activities that are interdependent in terms of start and end times and eventually converge. In this technique, the aim is to determine the critical path to be considered in order to reach the endpoint in the stipulated time and to examine the alternatives that will occur in case the activity durations change [25]. In order to understand CPM, some basic concepts should be known first. Project network is the visual that shows the activities and priority relationships in the project. Activity, any work that contributes to the completion of the project. A predecessor is an activity that must be completed before an activity can begin. ES is the earliest time an activity can start provided that all previous activities have been completed. Earliest Finish (EF) is the time found by adding the activity duration to the ES time of an activity. Latest Start (LS) is determined by subtracting the completion time of an activity from the LF. LF is the time found by adding the activity time to the LS time. Slack (S) is the time difference between the ES and LS or LF and EF times for an activity. The critical path is the path of critical activities that do not have slack time [26]. Any delay in critical activities delays the overall project completion time and the project should be managed in a way that avoids delays in any of these activities [27].

In CPM, which is one of the most widely used network methods today, the hierarchical structure of the activities in the project is determined and the process is planned according to the relationships between critical and non-critical activities and interconnected and unrelated activities. This method has many advantages such as not being mathematically complicated, having different application areas, tracking both time and cost.

2.2. Fuzzy Concept

Fuzzy logic, which was first introduced by Lotfi Zadeh [4] in 1965 and has survived to the present day, aims to describe objects and values closer to reality and more appropriately. The basic idea of this philosophy, which is called fuzzy set theory, is that the truth values (or membership values in fuzzy sets) for a judgment take not only 0 or 1 values as in the classical set approach, but also values ranging from 0 to1 and this provides the opportunity to evaluate all alternatives with the concept of likelihood [28]. Fuzzy set theory is a method that takes the solution process by formulating a model in which there is no precise information and subjectivity [14]. Fuzzy logic, while making a judgment

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about something, simultaneously talks about how much it is inside and how outside of the mathematical classifications on which it is based. Brings a new definition to that data based on the knowledge of how much the data belongs to that set of judgments and how much it does not [29]. In a fuzzy set A defined in the universal set, the membership μA; is stated as μA : E → [0,1]. For an element x in this fuzzy set A the membership degree is shown as Ã = {(x, μÃ (x)) | x∈ E)} [30].

Fuzzy numbers are expressed as a convex, normalized, finite-continuous membership function and defined as real numbers [31]. The membership function μÃ (x) : X → [0, 1] for a triangular fuzzy number Ã=(a, b, c) is defined as follows [32]:

$$\mu_{\tilde{A}}(x) = \begin{cases} \frac{x-a}{b-a}, & a \leq x \leq b \\ \frac{c-x}{c-b}, & b \leq x \leq c \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

2.3. Yager's Ranking Method

Yager [33] suggested the following procedure for ranking fuzzy sets. In addition to being robust, the Yager ranking index is a field swapping index with linearity and summability properties [8]. Let convex fuzzy number $\tilde{t}$ be defined as a fuzzy triangular number $\tilde{t}=(a, b, c)$. In this case, the ranking index $I(\tilde{t})$ will be as in Eq. 2 [34].

$$I(\tilde{t}) = \int_0^1 \frac{1}{2}(t_\alpha^L, t_\alpha^U) d\alpha \tag{2}$$

$\tilde{t}$ is the center of the mean value of the fuzzy numbers. Within the scope of this study, the ranking index formula presented in [14] and used in [21] was used to convert fuzzy numbers to crisp values. $\tilde{A}=(a, m, b)$ triangular fuzzy number, the ranking index $I(\overline{T}_{ij})$ was calculated with Eq. 3 for each activity in the process of converting fuzzy times to crisp values with Yager ranking method.

$$I(\overline{T}_{ij}) = \frac{a+m+b}{3} \tag{3}$$

Here $\overline{T}_{ij}$ =ij is the fuzzy duration of activity. The difference of this method from most other ranking methods is that it allows the crisp value return in cases where the membership degrees of uncertainty are not known [21]. The basis of Yager's ranking method is to convert the fuzzy CPM problem into the classical CPM problem with classical activity duration [14].

2.4. Experimental Analysis

The main steps in CPM include identifying the individual activities, determining the sequence of these activities, organizing the network diagram, estimating the completion time for each activity, and defining the critical path [35]. In this study, the programming of the Coordinate Measuring Machine (CMM) installation (assembly and purchasing process) project in the Mechanical Production Department of an enterprise is discussed. Table 1 lists the activities, their predecessors and their possible durations. Since the activity times cannot fully reflect the reality, they are considered as triangular fuzzy numbers instead of crisp values. This is easily explained; the setup of each machine is

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different and the department staff is not experienced in this field to provide the appropriate time under the most favorable conditions. Figure 2 shows the network diagram for the CMM project.

Table 1. The data of the considered project.

Activity no	**Name of the activity**	**Predecessors**	**Activity duration time (days)**
A	Deciding on the machine vendor	-	30
B	Shipping time	A	30
C	Storage of the machine until the arrival of technical sales personnel	B	45
D	Machine acceptance tests	C,J,L	2
E	Machine final assembly	D	2
F	Training of the related department engineer about the machine	E	7
G	Trial period	F	15
H	Technician internship	G	21
I	Supplier decision of ventilation (air conditioning) machine	A	60
J	Transport and assembly of the machine	I	30
K	Room design	A	15
L	Room construction	K	45

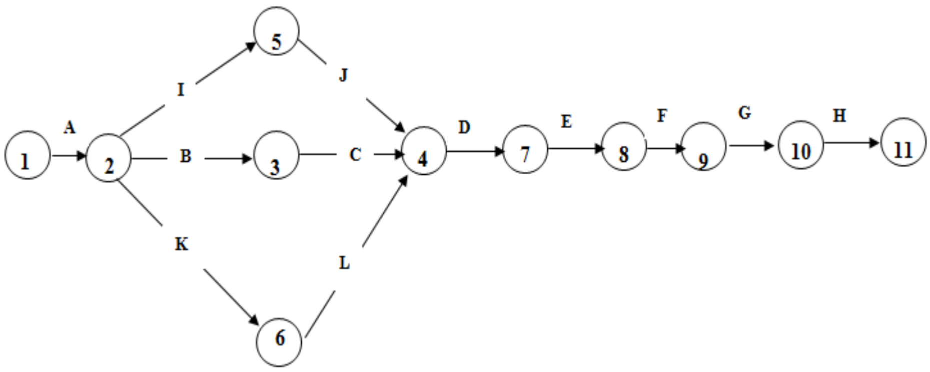

Figure 2. The network diagram of the analyzed Project.

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3. RESULTS

In the first stage, the project completion time and critical path are found by using these possible activity durations and logical relationships between activities. The results obtained are presented in Table 2. In Table 2, the first column shows the activity no, the second column shows the predecessors, and the third column shows the possible time. The fourth, fifth, sixth and seventh columns show the ES, EF, LS and LF durations of the activities, respectively. In order to be able to analyze the possible waits in the project, it is necessary to determine the slack time for each activity. Slack time; is the amount of time that a delay in the ES of a given activity does not disrupt the completion of the project. The gap time of a given activity can be calculated with = LS – ES = LF – EF. The eighth column shows the slack times. Activity without slack time; is called critical activity in the network. The ninth column shows the critical activities. According to these results, the project completion time was found to be 167 days and the critical path A – I – J – D – E – F – G – H.

Table 2. Analysis results according to possible values.

Activity no	**Predecessors**	**Activity time/days**	**ES**	**EF**	**LS**	**LF**	**Slack (LF-EF)**	**On critical path**
A	-	30	0	30	0	30	0	Yes
I	A	60	30	90	30	90	0	Yes
B	A	30	30	60	45	75	15	No
K	A	15	30	45	60	75	30	No
J	I	30	90	120	90	120	0	Yes
C	B	45	60	105	75	120	15	No
L	K	45	45	90	75	120	30	No
D	C,J,L	2	120	122	120	122	0	Yes
E	D	2	122	124	122	124	0	Yes
F	E	7	124	131	124	131	0	Yes
G	F	15	131	146	131	146	0	Yes
H	G	21	146	**167**	146	167	0	Yes

In the next stage, the project critical path and completion time were calculated by using the project activity times expressed with triangular fuzzy numbers given in Table 3. Triangular fuzzy numbers represent optimistic, possible and pessimistic situations as project duration. The possible activity duration is the activity duration used in the first stage, and similarly, the project critical path and completion time are calculated by performing the same operations for the values in other situations (best values and worst values). Afterward, triangular fuzzy numbers were converted to crisp values with Yager's ranking index and project completion time and critical path were found based on the obtained time values.

Table 3. Durations in the context of triangular fuzzy numbers and crisp values.

Activity no	Predecessors	Activity duration time (days)			
		Best	Possible	Worst	Crisp values (Yager ranking index)
A	-	21	30	36	29
B	A	25	30	40	31,67
C	B	30	45	50	41,67
D	C,J,L	1	2	4	2,33
E	D	1	2	3	2
F	E	4	7	10	7
G	F	12	15	20	15,67
H	G	16	21	30	22,33
I	A	50	60	72	60,67
J	I	18	30	40	29,33
K	A	10	15	22	15,67
L	K	35	45	50	43,33

The results obtained for all cases are presented in Table 4. As seen in Table 4, when triangular fuzzy numbers were used, only one critical path for the project was determined for all three durations and the project durations were obtained as (123, 167, 215 days). When the analysis is made according to the crisp values obtained with the Yager ranking index, the critical path is still the same, and the project completion time has been obtained as 168.33 ≈ 168 days. According to the data obtained from the enterprise, this project was actually completed in 196 days. It is seen that the actual completion time of the project takes much more than 167 days calculated according to possible values and 168 days calculated according to the crisp values, and even closer to the maximum value of the fuzzy project duration of 215 days.

Table 4. Calculation results.

Type of activity duration		Project completion time	Critical path
Fuzzy activity times	Best	123	A – I – J – D – E – F – G – H
	Possible	167	
	Worst	215	
Crisp values	Crisp values (Yager ranking index)	168,33	

Based on these results, it can be said that the fuzzy-valued CPM provides more information to the decision maker about the project completion time and that closer results to real-life can be obtained with the fuzzy logic method. As in the example discussed in this study, most real-life problems are inherently fuzzy. Even if all the conditions for the project process covered in the study are similar (such as employing personnel with the same experience and using the same equipment), the completion time of the activities may vary. For this reason, a real project process is handled with both fuzzy activity durations and crisp activity durations obtained by crisp value conversion. Completion times obtained using CPM for both cases were compared with the time the project was actually completed. The results obtained show the importance of using fuzzy-valued CPM.

4. DISCUSSION and CONCLUSIONS

In today's business world, the most effective management of projects and their completion within the stipulated time can affect the success and future of enterprise. In this context, a more realistic calculation of the completion time of the project can increase the success of the project management and thus the success of the enterprise. In today's highly competitive business environment, project management's ability to plan activities and track progress within strict cost, time and performance guidelines is becoming increasingly important to achieve competitive priorities such as on-time delivery and customization [36]. For example, in [37] the authors conducted a study on how to minimize aircraft maintenance planning time and how to create a plan with critical path analysis in a fuzzy environment. They concluded that if an aircraft maintenance operations and service system is inadequate or operational procedures are ineffective, these factors can cause flight delays that can be very costly for airlines in the long-term. Therefore, it can be said that the project planning and programming process allows the follow-up of projects not only in terms of time but also in terms of cost.

In this study, a real enterprise project is analyzed with CPM. In the study, due to uncertain situations that may arise from human and machine in project activities, crisp times could not be given and the concept of fuzzy logic was used. The use of triangular fuzzy numbers allows planning for the project by considering optimistic, possible, and pessimistic situations. In order to compare the results obtained from fuzzy CPM, crisp value conversion was performed with Yager ranking method . This method is preferred because it allows defuzzycation without the need to know the membership degrees. Yager’s ranking method is based on converting the fuzzy critical path problem into a classical critical path problem with crisp activity time [34]. Although the project critical path is the same in both cases, there is a difference in terms of project completion times. It has been determined that the crisp number conversion value is very close to the possible time, but it is between the possible time and the worst time. Considering the actual completion time of the project, it is seen that it is closer to the worst time. Considering the contributions of a more realistic calculation of the project completion time to the enterprises, the importance of the studies in this field is revealed.

The results obtained from the considered problem show how real-life uncertainties can affect programming results. In the study, a real project process, which has been completed beforehand and whose completion time is known, is discussed. This provides the opportunity to compare the project completion times calculated using fuzzy and crisp values with the actual completion time of the project. According to the results obtained, it is seen that the actual completion time of the project is closer to the maximum completion time calculated using the worst times. Therefore, in light of these results, it can be said that businesses can gain an advantage by including uncertainties in their planning in order to reduce the possibility of experiencing disruptions and delays due to programming that does not fully reflect reality and to avoid possible surprise results. Thus, this situation can make a positive contribution to businesses in terms of customer satisfaction and on-time delivery.

In future studies, project activity times can be expressed with different fuzzy numbers (L-R type, neutrosophic, trapezoidal, decagonal, etc.) and the results obtained using different defuzzification techniques for crisp value conversion can be compared. In addition, CPM can be considered in a stochastic network to express the uncertainty in activity durations.

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