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A Fuzzy Cognitive Map Approach Applied in Cost–Benefit Analysis for Highway Projects

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Abstract Cost–benefit analysis (CBA) is a method widely used all over the world for transport project appraisal. However, this method needs to handle the inherent uncertainty which affects the results negatively. In a highway project, there are high uncertainties due to a lack of data, future predictions, economic indeterminacy, etc. In conventional approaches, a risk analysis, which is based primarily on a sensitivity analysis and/or Monte Carlo simulation, is conducted in order to solve the problems mentioned above. However, these approaches present some main drawbacks. This study aims to investigate the usability and utility of a new approach in highways CBA in order to cope with uncertainty easily and in a more user-friendly way. To achieve the above-cited goal, the technique of a fuzzy cognitive map (FCM) was utilized due to its popularity in modeling complex problems. A decision-making FCM model including a RISK parameter was developed by experienced people/experts in this scientific domain to assess benefits and costs in highway projects. The developed FCM model focuses on minimizing the effects of uncertainty in the CBA for highways. Therefore, the concepts of conventional CBA were defined within the domain of risk analysis. The performance of the developed FCM model was tested through actual feasibility studies as well as through a specific case study. As a result of comparisons, promising results for validation of the developed FCM model are obtained.

Keywords Cost–benefit analysis · Decision making · Fuzzy cognitive map · Fuzzy risk analysis · Highway projects · Transport economic appraisal

1 Introduction

The most extensively used economic appraisal method for transportation projects is CBA [17]. CBA is a technique for assessing costs and benefits of a capital investment project over a given time period [43]. It is widely used in business and government spending project assessment. It proves to be an easy-to-understand technique for relevant users. Its clarity gives the possibility to everyone to understand the monetary nature of an investment project. CBA is a helpful technique for decision making on the feasibility of an investment project [7]. However, this method has some important disadvantages such as the following: requirement of a large amount of data for analysis; collection of systematic data with no missing values; prediction of the costs and benefits in the analysis period, etc. In the case of a failure to cope with the mentioned uncertain situations, high-cost investments are faced with the risk of wrong decision making.

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In CBA for highways, SA is a well-established technique for the aforesaid undetermined variables and uncertainty [14]. In SA, each critical parameter, existing within the system, is evaluated by focusing on best-/worst-case scenarios. The analysis is carried out by varying one element at a time and determining the effect of that change on the benefit–cost rate. Under standard SA, the influence of each variable on the project outcome is analyzed separately [12]. This process is time-consuming, due to the need of a very large number of separate analyses to be accomplished. Furthermore, many discrete analyses cause difficulties in the interpretability of the results for decision making.

There are a relatively large number of studies reported in the literature for assessing highways CBA. A number of researchers have focused on selecting highway projects with CBA by using deterministic approaches [11, 13, 15, 19, 25], fuzzy multi-objective programming [41], fuzzy logic [4, 23] and fuzzy analytic hierarchy process [26]. These studies have not assessed, efficiently, the uncertainty in highways CBA, when taking into account all the risks. Besides these, there are certain studies focusing on handling uncertainty and its influences. These studies use MCS approach in risk analysis of highways CBA [35–38, 44]. This approach is based on stochastic calculations assigning probability distributions to the uncertain variables. Even though MCS provides a helpful way of performing risk analysis, this proves to be a difficult and time-consuming process, due to the assignment of probability distributions individually to each variable, based on the best-available knowledge.

Based on the aforementioned issues, a new approach, taking into account all the influences in question simultaneously, is needed to minimize the loss of time and show overall influences of uncertainty on CBA. Moreover, an approach considering and integrating engineering experience and expert knowledge is needed, in order to strengthen the decision-making mechanism, without the need of a large amount of data for analysis. In this study, the main objective is the investigation of the usability and utility of a soft computing approach for highways CBA in order to cope with the inherent uncertainty, without undue delays, while providing at the same time, comprehensible results for decision makers. This is all to say that a new approach having following properties is needed: (1) ease to handle, (2) low time-consuming and (3) ability to analyze all the risks simultaneously. In order to fulfill the goal of this study, the technique of FCM was investigated for modeling and decision making of CBA. Therefore, a FCM model was developed to cope with the effects of uncertainty in CBA. FCM forms a field of intelligent modeling and computing that has gained constantly increasing research interest in the last 20 years. FCM introduced by Kosko [20] as an extension to cognitive maps [3] has been applied in a wide range of research areas such as engineering; medicine; politics; environment; economics; and management [29]. Also, a number of FCM modeling methodologies and/or FCM extensions for modeling systems have been proposed [30].

The popularity of FCM stems from the fact that they offer a series of advantages to researchers, including their ease to construct and use, their flexibility and adaptation to practically any problem domain, their ability to execute fast, their relatively simple and comprehensible modeling philosophy which is very close to human reasoning and their capabilities to handle complex issues efficiently in environments with uncertainty. The aforementioned advantages essentially fed the enormous explosion of the utilization of FCM in a number of applications in different areas and may nowadays be recognized as one of the most promising scientific fields in modeling complex systems [29].

The remainder of the paper is organized as follows: Sect. 2 describes the principles of conventional CBA on highway projects; Sect. 3 describes the principles of sigmoid FCM; Sect. 4 describes the main steps in developing the FCM model for highways CBA; Sect. 5 presents the simulation analysis; Sect. 6 shows comparative results of the developed model with the conventional approaches; and Sect. 7 concludes the paper by discussing relevant remarks and further research aspects that need to be considered in the future.

2 Overview of Cost–Benefit Analysis for Highway Projects

The economic analysis of highways is mainly based on two pillars: The first one concerns “costs” which are composed of expenses starting from the project initiation to the end of the analysis period; the second one concerns “benefits” which consist of monetary values of social benefits expected during the project evaluation period [14]. The main concepts of highways CBA are as follows: (1) highway agency costs (costs); construction costs (CC); operating and maintenance costs (OMC); (2) road users' costs (benefits): time value (TV); accident costs (AC); vehicle operating costs (VOC).

The benefits and costs indicated above are discounted to net present values by the application of a suitable discount rate [24]. The discounting process is as follows:

$$P = F(1/(1+i)^n) = F(P/F, i, n) \quad (1)$$

where P is the present value of money, n is the evaluation period and i is the discount rate. F is the future value of money at the end of the nth period. The $(1/(1 + i)^n)$ factor is known as the single-payment present-worth factor and is designated as the (P/F) factor. This factor is also referred to as the discounting factor, and the process is known as the discounting process [1]. The economic discounting process and the decision rule for highways CBA and B/C ratio are denoted by Eq. (2).

$$P_{\text{Benefits}} = \sum_{t=1}^{n} \frac{F_{t\,\text{AC}}}{(1+i)^t} + \sum_{t=1}^{n} \frac{F_{t\,\text{TV}}}{(1+i)^t} + \sum_{t=1}^{n} \frac{F_{t\,\text{VOC}}}{(1+i)^t}$$

$$P_{\text{Costs}} = \sum_{t=1}^{n} \frac{F_{t\,\text{OMC}}}{(1+i)^t} + P_{\text{CC}} \tag{2}$$

$$\text{Decision}(x) = \begin{cases} \text{reject}, & x < 1 \\ \text{accept}, & x \geq 1 \end{cases} \qquad x = \frac{P_{\text{Benefits}}}{P_{\text{Costs}}}$$

In Eq. (2), all the benefits and costs are discounted to the present value. B/C rate is obtained. In order to accept the project, the ratio has to be ≥ 1. The most important point of the analysis is that the data related to AC, TV, VOC, CC and OMC have to be evaluated without including ambiguities if possible [5].

3 Fuzzy Cognitive Map

FCM plays an important role in defining and modeling complex systems. FCM reveals a solution, depending on human experience and knowledge, in the direction of the dynamics of the system and against variations in conditions. With this structure, the method is widely and effectively applied in decision-making analyses. FCM consists of the conceptual variables of the nodes (the elements composing the system) and the lines between the nodes, having both direction and weights, showing the relations between the conceptual variables [42]. In FCM the conceptual variables take values within the range of $\|0, 1\|$. The relations between conceptual variables, C_i and C_j, are of three different types: positive; negative; and no relationship. The value of W_{ij} shows how strongly the C_i conceptual variable influences the C_j conceptual variable [27]. After defuzzification, the weighted relations take a value in the $\|-1, 1\|$ range [16]. The conceptual variable value (A_i) for each conceptual variable is calculated with Eq. (3):

$$A_i^t = f\left(\sum_{\substack{j=1 \\ j \neq 1}}^{n} A_j^{t-1} W_{ji} + A_i^{t-1} \right) \tag{3}$$

A_i^t gives the value of C_i conceptual variable at time t, A_j^{t-1} gives the values of C_j at time $(t-1)$, W_{ji} is the influence value to C_i from C_j conceptual variable; and f is the threshold function [39]. The most used threshold function for the FCM is given in Eq. (4):

$$f(x) = \frac{1}{1 + e^{-\lambda x}} \tag{4}$$

The development and design of the appropriate FCM for the modeling of a system requires the contribution of human knowledge. Usually, knowledgeable experts, who are familiar with the FCM formalism, are required to develop a FCM using an interactive procedure of presenting their knowledge on the operation and behavior of the system [29].

4 Developed FCM Model

The developed FCM model focuses on minimizing the effects of uncertainty in the CBA for highways. Therefore, the concepts of conventional CBA were defined within the domain of risk analysis [5]. The preliminary methodology of FCM [29] was used in this study. A literature survey supports that the FCM method has the ability to fulfill the necessities for the development of the model. A RISK parameter was added to the model to make a structure able to minimize the negative effects of uncertainty. The new model contains seven concepts which are the fundamental concepts of conventional CBA, namely AC (C_2); TV (C_3); VOC (C_4); OMC (C_5); CC (C_6); benefit/cost rate (C_7); and the RISK parameter (C_1). The construction of the model is shown in Fig. 1.

Figure 1 shows that the concepts of conventional CBA for highway projects were defined within the domain of risk analysis by means of RISK parameter.

4.1 Determining the Weights Between the Concepts of CBA and B/C rate

The FCM is a dynamic discrete system in which there are cause–effect relationships between the concepts and these

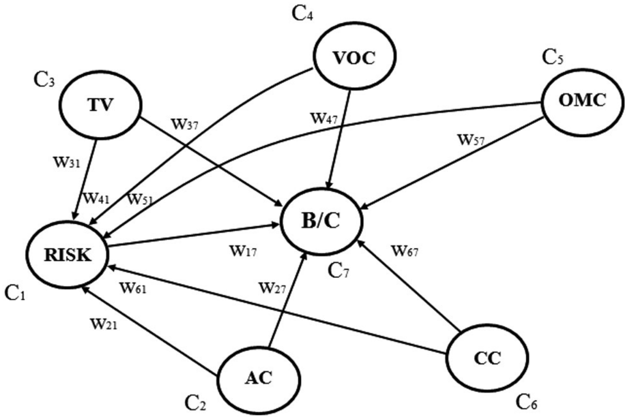

Fig. 1 FCM of the new model

causal interconnections are weighted [10]. The determination of the weighting between the concepts is one of the most important phases of the model development. There are many approaches and methods in the literature in this respect. In this paper, a fuzzy rule base approach is chosen due to its efficient solution of the problem [31–33]. In this approach, the effects between the concepts are put forward as a result of the evaluation of experts views. Firstly, the concepts and the effects between the concepts are fuzzified. The fuzzified illustrations are shown in Fig. 2.

The transactions of fuzzifying the concepts were executed by experienced experts in the field of highway economy. The fuzzy sets in Fig. 2 were defined by the experts taking into consideration Turkish transportation conditions. The concepts in the model are fuzzified with the triangular membership functions as very low; low; moderate; high; and very high. Since the concepts shown in Fig. 2 have linearly increasing value ranges, they can easily be adapted to applications with different scales. Upon fuzzifying the concepts, it is also necessary to fuzzify the cause–effect relationships between the concepts. These relationships among the concepts, due to the structure of the FCM, have to be in the range of $\|-1, 1\|$ [18]. The fuzzifying process of the effect values between concepts in the FCM is shown in Fig. 3. The concepts shown in Fig. 3 are fuzzified using triangular membership functions which are denoted as "negative extreme strong (NES), negative very very strong (NVVS), negative very strong (NVS), negative strong (NS), negative strongly medium (NSM), negative weakly medium (NWM), negative weak (NW), negative very weak (NVW), negative very very weak (NVVW), negative extreme weak (NEW), positive extreme weak (PEW), positive very very weak (PVVW), positive very weak (PVW), positive weak (PW), positive weakly medium (PWM), positive strongly medium (PSM), positive strong (PS), positive very strong (PVS), positive very very strong (PVVS) and positive extreme strong (PES)." Figure 3 shows that the effects between concepts were fuzzified. A large number of membership functions were applied in order to increase sensitivity level of the developed model.

It is necessary to establish a rule base in order to determine the weight values between concepts together with the fuzzifying process [9]. The rule base in this study is established by three experts having experience in the economic evaluation of transport projects and knowing the main aspects of fuzzy logic. For example, the experts' opinions for the evaluation of the effects between concepts are as follows:

Expert 1 If a very high increase in the value of AC occurs then a very small positive increase happens in the value of benefit/cost rate. Inference; the influence from C_2 to C_7 is PVW.

Expert 2 If a very high increase in the value of AC occurs then a very small positive increase happens in the value of benefit/cost rate. Inference; the influence from C_2 to C_7 is PVW.

Expert 3 If a very high increase in the value of AC occurs then a small positive increase happens in the value of benefit/cost rate. Inference; the influence from C_2 to C_7 is PW.

The rules between the concepts, which are in interaction with each other, are established by each expert. These rules are then combined and accordingly the weight value is calculated [28]. The linguistic inferences "PVW, PVW, PW" representing the triangular membership functions were summed using an aggregation operator. Here, contrary to the min–max method, which is used in a conventional fuzzy logic approach, SUM technique is utilized. The SUM technique sums up all the triangular functions with equal contributions [27]. Figure 4 shows the aggregation of the experts' opinions and the determination of a weight value defining the strength of the relationship between the two concepts. Each one of the triangles in

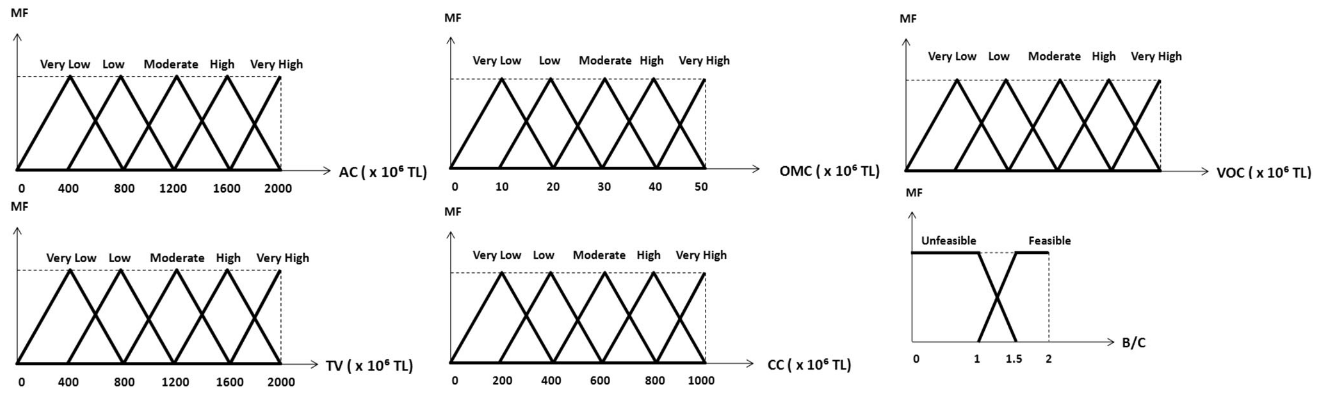

Fig. 2 Fuzzifying the concepts

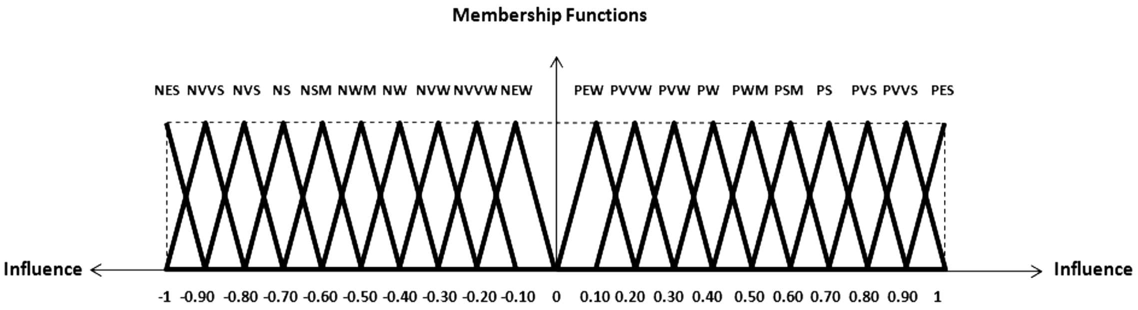

Fig. 3 Fuzzifying the effects between concepts

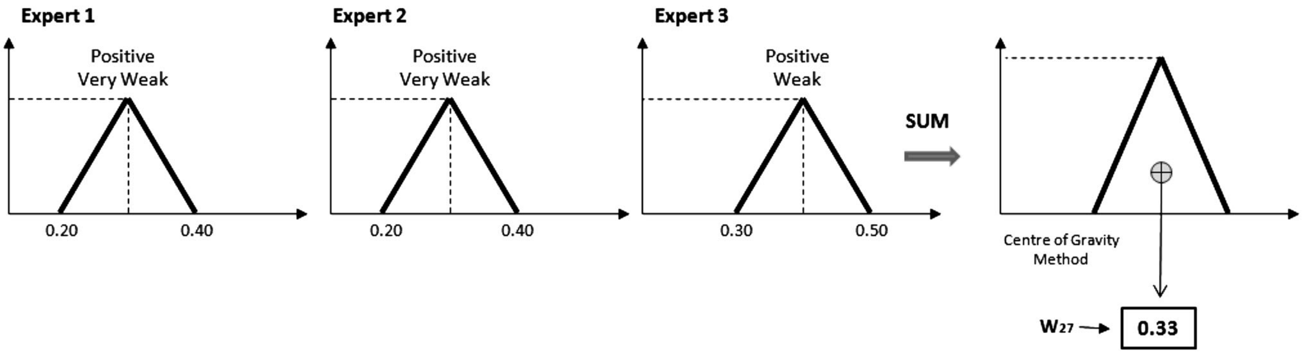

Fig. 4 Fuzzy aggregation of expert opinions and defuzzification

Fig. 4 is derived from Fig. 3 and describes a membership function corresponding to a linguistic variable that assesses the degree of influence between the concepts C_2 and C_7. The three membership functions (PVW, PVW and PW) were summed, and an overall linguistic weight was produced (also in Fig. 4) which, through the defuzzification method of center of gravity, was transformed into the numerical value of $w_{27} = 0.33$ (describes the strength of relationship between concept C_2 and concept C_7).

As shown in Fig. 4, an overall linguistic weight $C2 \Rightarrow C7$ is produced through the defuzzification of the center of gravity from the fuzzy logic. Overall linguistic weights between concepts are produced through the defuzzification of the center of gravity from the fuzzy logic. All of the effects of $C_2 \Rightarrow C_7$, $C_3 \Rightarrow C_7$, $C_4 \Rightarrow C_7$, $C_5 \Rightarrow C_7$, $C_6 \Rightarrow C_7$ in the system were calculated in this manner. Therefore, the FCM model of the CBA is constructed and the weight values between concepts are defined.

4.2 Determining the Weights Between the Concepts of CBA and RISK Parameter

The traditional risk steps [8] (identification, description, estimation and evaluation) were followed in the process of the inclusion of the RISK parameter into the system. The risks corresponding to the CBA for highways were identified and determined through a literature survey. Three expert opinions were used for the estimation of the risks. The evaluation of the risks was done by using fuzzy risk analysis. The "Appendix" shows the risk descriptions of CBA of Turkish highways. The risk impact value is a function of risk severity and risk likelihood [34], so the descriptions are given as risk likelihood and risk severity. The risk likelihoods were expressed in linguistic variables as "very unlikely, unlikely, medium, likely, very likely" and the risk severity was expressed as "very low, low, medium, high, very high." The risk impact was expressed as "ignorable, low, medium, high, critical." All the linguistic variables were converted to fuzzy triangular functions within the range of ‖0, 1‖. Figure 5 depicts the fuzzy sets of risk likelihood, risk severity and risk impact. The number, range and shape of membership functions for risk likelihood and risk severity can vary depending on the size and type of study in each highway CBA. For simplicity and generalization, five triangular membership functions were defined with uniform partition for risk likelihood, risk severity and risk impact in this study.

A fuzzy rule base is needed in order to determine the relationships between fuzzified parameters [9]. The fuzzy rule base used in this study was obtained from a previous study proposed by Lazzerini and Mkrtchyan [21]. The fuzzy rule base for the developed CBA model is shown in Table 1.

The experts were opined on the risk likelihood and severity for each concept in the developed CBA model.

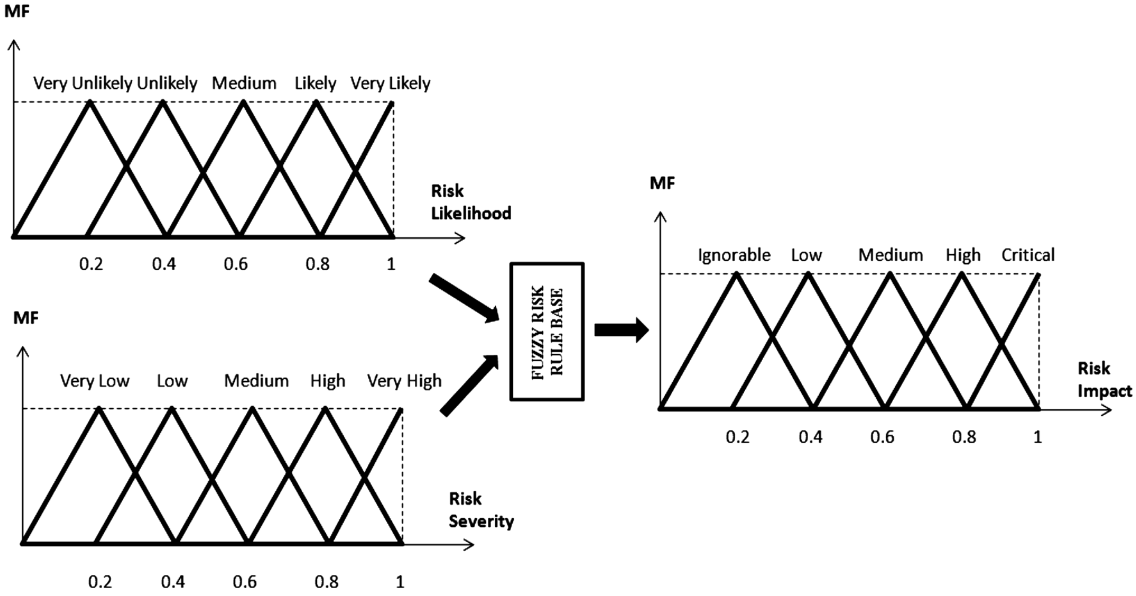

Fig. 5 Fuzzy functions of risk likelihood, risk severity and risk impact

Therefore, risk impact values were produced in the form of fuzzy linguistic values of "ignorable, low, medium, high, critical" by pooling the experts' linguistic expressions as denoted in the fuzzy rule base. Summarizing the steps of the risk process are: (1) identification of all the risks in highways CBA taking into account severity and likelihood (see "Appendix"); (2) assigning linguistic values to all the described risks by the experts; (3) conversion of experts' opinions about the likelihood and severity of the risks to fuzzy membership functions; (4) producing risk impact value in the form of a fuzzy membership function assigned by each expert for each risk using the fuzzy rule base in Table 1. In the next step, the fuzzy triangular functions that represent risk impact were summed by using an aggregation operator. After summation, the defuzzification was performed to produce a risk weight value. Figure 6 shows the aggregation of the fuzzy triangular functions that represent risk impacts obtained from experts' opinions and how the numerical value of the risk weight was obtained.

Figure 6 depicts the effect of the risk parameter on the VOC concept and the calculation of its weight value. Experts responded to the severity and likelihood questions about each risk. Then, the assigned triangular functions that represent the risk impact for each risk were considered through the fuzzy rule base. These triangular functions were summed by utilizing an aggregation operator.

In this study, the approach developed by Lazzerini and Mkrtchyan [21] for aggregation of risks was used. Lazzerini and Mkrtchyan [22] studied the pessimistic approach instead of traditional aggregation operators for fuzzy risk models. They claimed that the pessimistic approach gives better results compared to the other aggregation techniques for fuzzy risk analysis. The conclusion of this approach is based on the worst-case expert opinion and ignores the others' opinions. The worst-case fuzzy triangular function for each risk is becoming its overall risk. All the risks are summed twice. In the first aggregation the fuzzy functions, that represent the experts' opinions, are summed using pessimistic approach for each risk. In the second aggregation, all the risks for each concept such as AC, VOC, etc., are summed to an overall risk function obtained from each risk by using SUM technique. As a result of this aggregation process, a total risk fuzzy membership function is produced. Lastly, a numerical weight value is obtained after applying center of gravity which is a fuzzy logic defuzzification method. In the developed CBA, the cause–effect relationships between the RISK parameter and the other concepts are calculated in this manner. All the resulted weight values are transformed into an adjacency matrix for simulation of the developed method. This is shown in Table 2.

5 FCM Model Simulation

The steps of FCM simulation are identified as follows: (1) Initial values of the concepts in the model are normalized and a row matrix which is expressed as "initial vector (*A*)" is generated from the normalized values before FCM simulation. (2) The final vector which is obtained from the multiplication of the adjacency matrix and initial vector is updated by Eqs. (3) and (4) during simulation. The new vector then becomes the initial vector in the following iteration of the system. The simulation is repeated until

Table 1 Fuzzy risk rule base

Severity	Likelihood				
	Very unlikely	Unlikely	Medium	Likely	Very likely
Very low	Ignorable	Ignorable	Ignorable	Low	Low
Low	Ignorable	Ignorable	Low	Medium	Medium
Medium	Ignorable	Low	Medium	High	High
High	Low	Medium	High	High	Critical
Very high	Low	Medium	High	Critical	Critical

Table 2 Adjacency matrix

Adjacency matrix		Risk	AC	TV	VOC	OMC	CC	*B*/*C*
Risk	*C*1	0	0	0	0	0	0	−0.56
AC	*C*2	0.48	0	0	0	0	0	0.33
TV	*C*3	0.69	0	0	0	0	0	0.40
VOC	*C*4	0.55	0	0	0	0	0	0.50
OMC	*C*5	0.20	0	0	0	0	0	−0.10
CC	*C*6	0.20	0	0	0	0	0	−0.87
B/*C*	*C*7	0	0	0	0	0	0	0

$A^t - A^{t-1} \leq e = 0.001$. (3) After simulation, the results are interpreted through a decision criterion. The decision criterion for the problem in this study is defined in Eq. (5) in order to evaluate the results after the simulation:

$$R(x) = \begin{cases} 0, & x < 0.5 \\ 1, & x \geq 0.5 \end{cases} \quad x = A^f(7) \tag{5}$$

According to the decision criterion, in this study, it is assumed that if the 7th value which is the decision-making concept in the final vector (A^f) is ≥0.5, the project is considered to be feasible; when this value is <0.5, the project is considered unfeasible.

To investigate the usability of the developed FCM model, it was compared with actual highway feasibility reports in Turkey. The summary results of the feasibility reports belonging to six different highway projects obtained from Turkish transportation authorities are shown in Table 3. These feasibility studies were implemented in previous years in Turkey. As shown in Table 3, the results of CBA were defined as "feasible" because of $B/C \geq 1$ and "unfeasible" because of $B/C < 1$ using Eq. (2) based on the reported feasibility studies. In order to perform simulations for the developed FCM model for the below feasibility studies, the values in Table 3 were normalized within the range of ||0, 1||. Next, one case of the below feasibility studies is analyzed as follows.

5.1 Feasibility Study (1): (Unfeasible Case)

The values of benefits and costs, for this case study, were normalized as follows: the value of the concept "AC", with a real value 69×10^6 TL, was calculated as 0.035 after normalization ($C_2 = 0.035$). The same process was followed by all the other concepts. The value of the concept "TV" is $C_3 = 0.185$; the value of the concept "VOC" is $C_4 = 0.188$; the value of the concept "OMC" is $C_5 = 0.706$; and the value of the concept "CC" is $C_6 = 0.83$. Thus, the initial vector for FCM simulation is denoted as: $A = [1\ 0.035\ 0.185\ 0.188\ 0.706\ 0.830\ 0]$. Through the FCM simulation process, the system converges to a steady state after 11 iterations with the final vector: $A^f = [0.0163\ 0.035\ 0.185\ 0.188\ 0.706\ 0.830\ 0.2366]$. The final value of decision concept, *B*/*C* rate, $A^f(7) = 0.2366$ was obtained. As can be implied from the criterion $R(x)$, the project is unfeasible. $R(x) = A^f(7) < 0.5 \rightarrow$ the project is unfeasible. The result of the feasibility report obtained from transportation authority is $B/C = 0.94 < 1$ meaning that the project is determined to be "unfeasible." The decision provided by the developed FCM model concurs with the decision provided by transportation authority as an "unfeasible" one for the same project.

The feasibility studies (2)–(6) were also calculated and evaluated by a similar manner, and all the results are shown in Table 4. The results of the conventional CBA for the six feasibility studies obtained from the Turkish transportation authorities and the FCM model are presented comparatively in Table 4.

It is observed that the final decisions of the developed FCM model concur with those produced by the conventional approach. This is a promising result in terms of the usability of the developed model and therefore justified further investigation. The developed model could not be compared with the results of SA because of a lack of data for these feasibility studies. Therefore, to evaluate the performance validity of the developed model a case study was executed.

6 Case Study

A case study was conducted in order to validate the performance of the developed model. To prove the performance accuracy of the proposed FCM method, its decision

Table 3 Highway feasibility studies

Feasibility study	Benefits ($\times 10^6$ TL)			Costs ($\times 10^6$ TL)		Result	
	AC	TV	VOC	OMC	CC	*B*/*C*	Decision
1	69	369	375	35	830	0.94	Unfeasible
2	121	135	152	26	385	0.99	Unfeasible
3	125	224	286	16	189	3.1	Feasible
4	85	68	74	6	120	1.8	Feasible
5	458	346	332	28	216	4.6	Feasible
6	650	490	520	21	191	7.8	Feasible

Table 4 Comparative results of developed model and conventional CBA

Study	Conv. *B*/*C*			FCM model			Comparison
	Result	Decision criterion	Decision	Result	Decision criterion	Decision	
1	0.94	$B/C < 1$	Unfeasible	0.2366	$A^f(7) < 0.5$	Unfeasible	Concur
2	0.99	$B/C < 1$	Unfeasible	0.4914	$A^f(7) < 0.5$	Unfeasible	Concur
3	3.1	$B/C > 1$	Feasible	0.7082	$A^f(7) > 0.5$	Feasible	Concur
4	1.8	$B/C > 1$	Feasible	0.7017	$A^f(7) > 0.5$	Feasible	Concur
5	4.6	$B/C > 1$	Feasible	0.7341	$A^f(7) > 0.5$	Feasible	Concur
6	7.8	$B/C > 1$	Feasible	0.811	$A^f(7) > 0.5$	Feasible	Concur

results were compared with conventional methods. To achieve that goal, the steps of the study methodology are defined as follows: (1) an actual feasibility study through which all the data and information can be accessed was investigated with the purpose of focusing on uncertainty influences; (2) SA, MCS and FCM modeling were performed for the feasibility study. All the results were compared with results of the developed FCM model; (3) various scenarios were considered by means of a traffic simulation program for the feasibility study. The results of the developed model were compared with the conventional approach for each scenario.

The case study chosen is a highway under construction (New Road) which is located in Dilovası district, Kocaeli Province in Turkey. It connects the North Marmara Motorway (NMM) with the Trans European Motorway (TEM), the State Highway (D100) and the İzmit Bay Crossing. The simplified illustration of the project is shown in Fig. 7. The project consists of a 10-km-long, 2 × 3 highway, a 1-km-long viaduct, two tunnels, four interchanges and one toll area. The construction cost of the project, which includes many transportation constructions, is notably high. It is foreseen that the project will be tendered in 2016 and opened to traffic in 2019. In this study, the project was analyzed using conventional CBA and determined as "feasible" [6].

The analysis is summarized as follows: (1) the construction cost was calculated by using current unit price analysis of the General Directorate of Turkish Highways in Turkey; (2) the OMC were determined by means of data obtained between the years 2003 and 2013 from other highways located in the same district; (3) the traffic data were obtained from the transportation master plan prepared by Kocaeli Metropolitan Municipality for the Greater Kocaeli area. The data, covering the years within 2016–2036, were produced by using the PTV Visum 13 traffic simulation program. In this program, scenario analysis was performed by consideration of two cases, the implementation and non-implementation of the project. All vehicles were converted into unit cars in the simulations and calculations; (4) the AC were calculated based on accident reports acquired from the Gendarmerie Command in the district. Accident estimation models were developed by means of data obtained by using least squares methods in SPSS 15.0 program. The accident estimations between the years 2016 and 2036 were produced by using this model; (5) a TV was determined by the Kocaeli Metropolitan Municipality for the transportation master plan of the Greater Kocaeli Area; and (6) an 8 % discount rate used in this analysis corresponds to the same percentage utilized by the Turkish transportation authorities in their economic evaluation of highway investments.

The way in which the results of the case study are obtained is as follows: (1) in line with above information, all data belonging to highways shown in Fig. 7 such as traffic flow, car speeds, accidents, etc., were identified on the PTV Visum 13 traffic simulation program; (2) the simulation program was run for both cases, in which the New Road is built or not built, considering a 20-year period. Both cases were then compared with each other; (3) in the case of the implementation of the New Road, in the economic analysis period, economic recovery as a result of

Table 5 Results of economic feasibility study

Costs (TL)		Benefits (TL)			Discount rate (%)	*B*/*C*	Result decision
CC	OMC	VOC	AC	TV			
402,443,718	18,312,000	275,858,772	51,848,916	228,682,265	8	1.32	*B*/*C* >1 The project is feasible

TL Turkish Lira

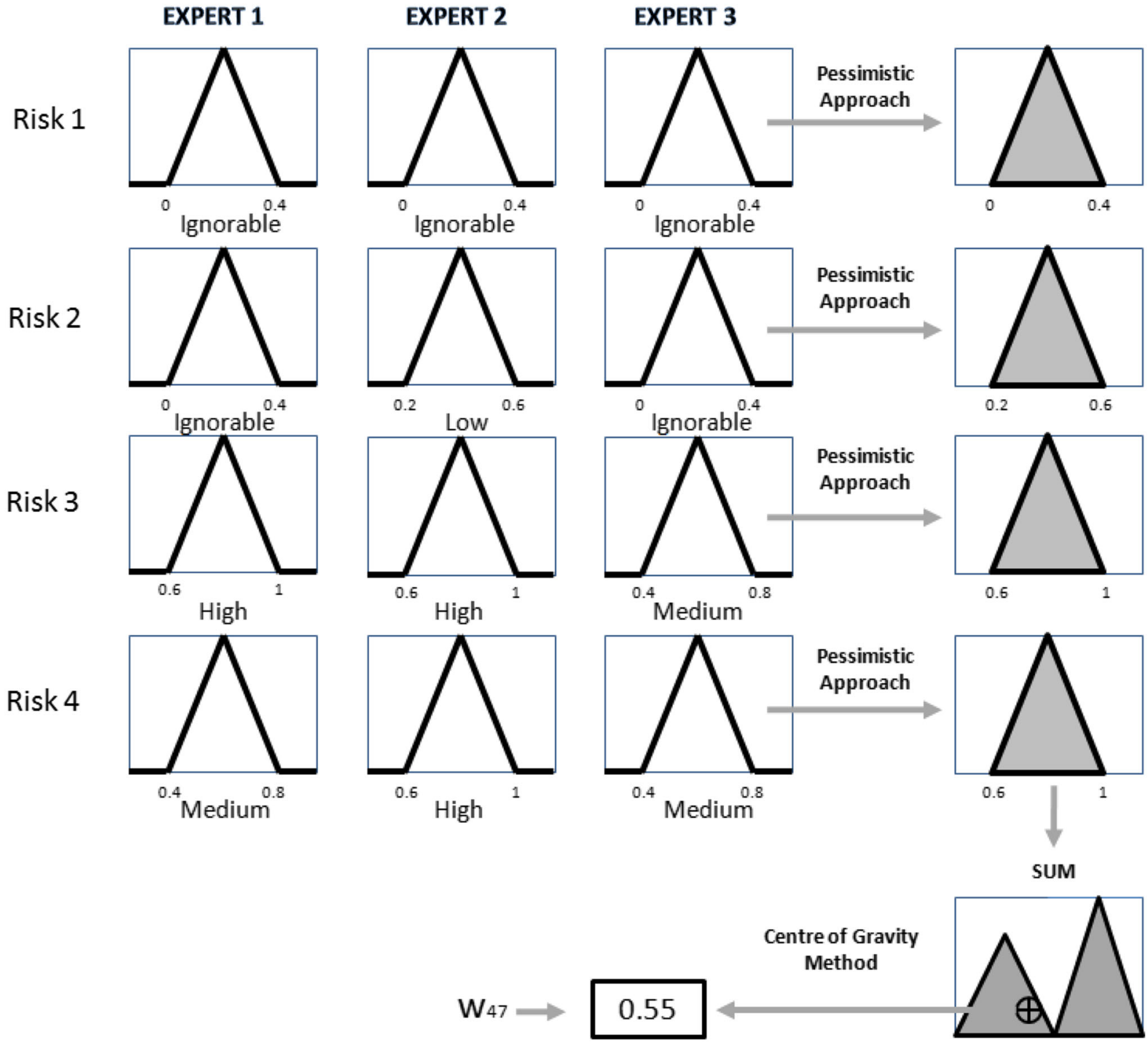

Fig. 6 Aggregation of risk impacts obtained from experts' opinions about risks of VOC and overall risk impact value

decreasing traffic accidents in the highways shown in Fig. 7, decreasing travel time of the highway users and decreasing VOC of highway users were computed. In summary, AC, TV and VOC were calculated; (4) initial costs and maintenance costs of the New Road were calculated; (5) finally, the conventional CBA was applied using Eq. (2). The results of the economic feasibility study which covers the 20-year period from 2016 to 2036 are

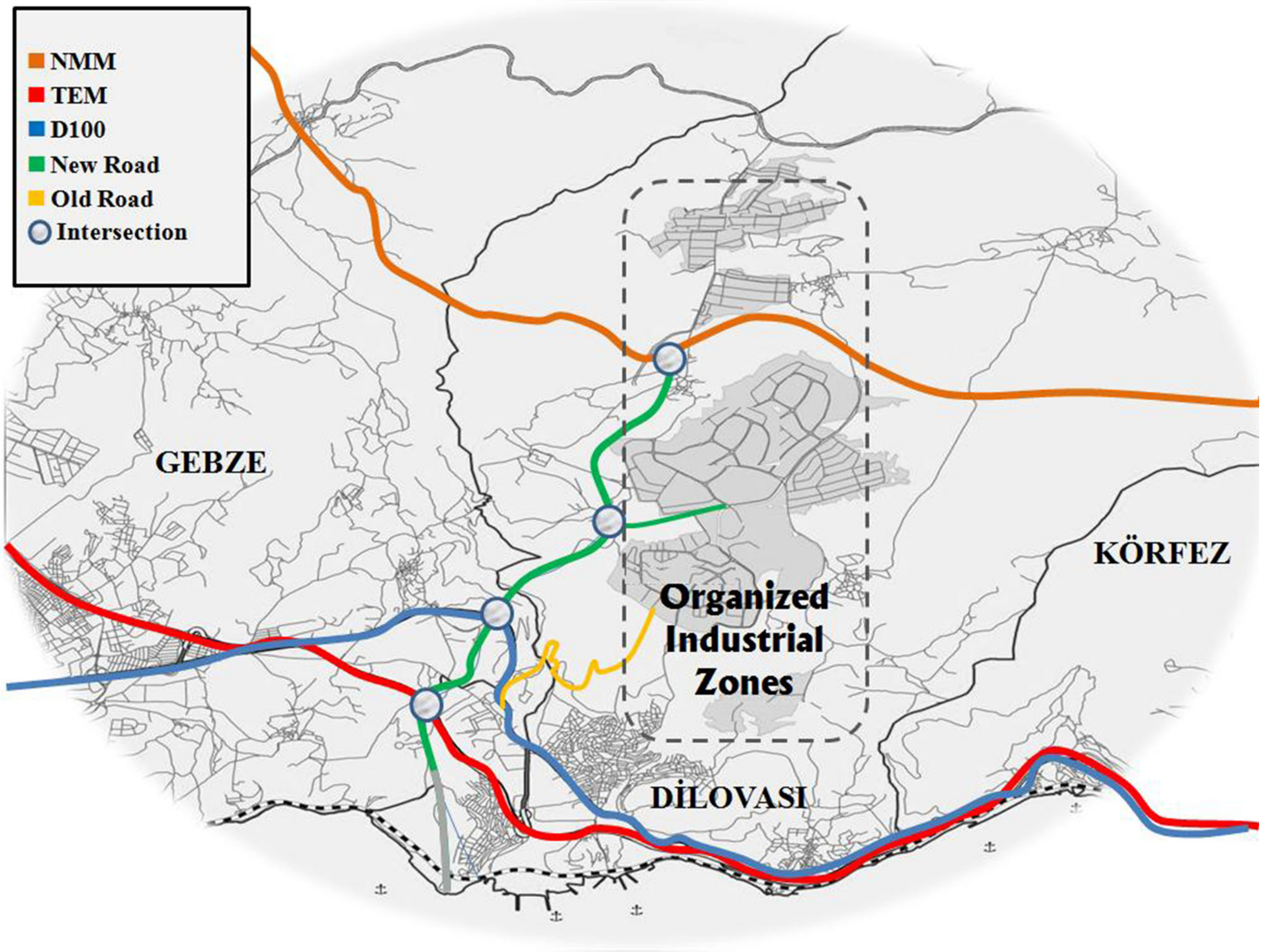

Fig. 7 Location of the New Road case study

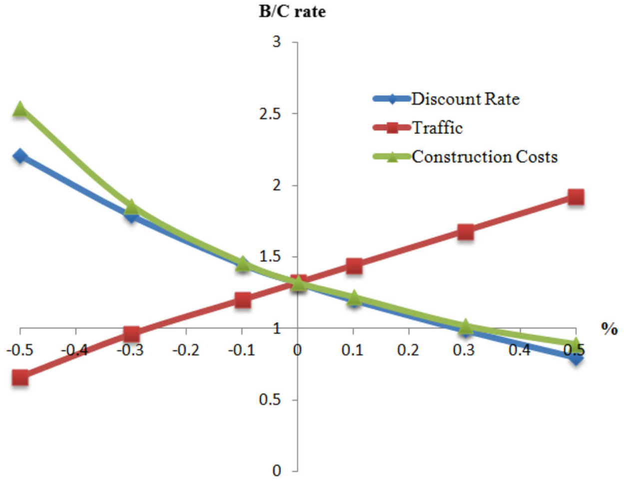

Fig. 8 Sensitivity of the critical parameters

shown in Table 5 [2, 6]. This case study has been previously proposed and investigated by the authors [2], and the validity of the case study was accepted by Ministry of Transport, Maritime Affairs and Communication (the supreme authority for highways in Turkey).

After the deterministic calculation, a SA was performed for risk analysis of the proposed case study. SA is mainly used in CBA in order to perform risk analysis considering uncertainty. It allows the analyst to subjectively get a feel for the impact of the variability of individual inputs on overall CBA results [14]. However, it causes difficulty on capturing effects of uncertainty among several variables at once, as combinations of discrete input changes require a very large number of separate analyses, since, the analysis is carried out by varying one element at a time and determining the effect of that change on B/C rate. The procedure followed to conduct the SA includes the following steps: (1) identification of variables; (2) elimination of deterministically dependent variables; (3) elasticity analysis; and (4) choice of critical variables [12]. Following this procedure, the Turkish transportation authorities have determined the critical parameters of the SA as discount rate; traffic; and construction cost [40] This study

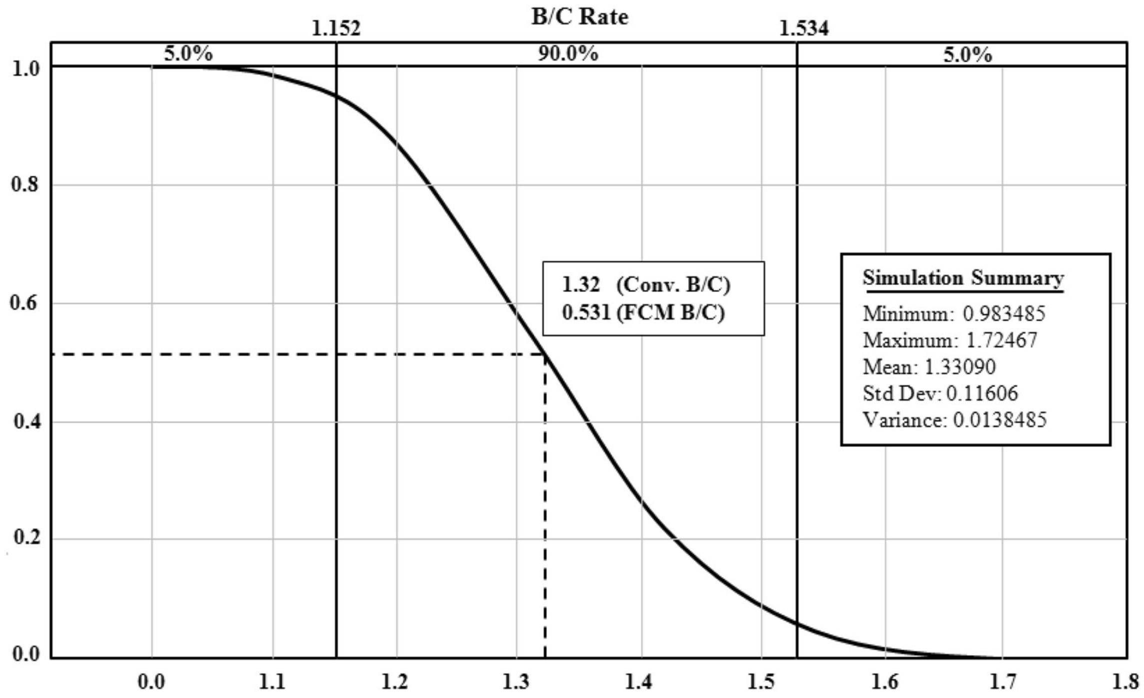

Fig. 9 Accumulated descending graph illustrating the variation of the *B*/*C* rate

Table 6 Results of conventional *B*/*C* and FCM model

Critical parameters	Range (%)	Conv. *B*/*C*		FCM model		Verification
		Result	Decision	Result	Decision	
Discount rate	50	0.80	Unfeasible	0.497	Unfeasible	✔
	30	0.99	Unfeasible	0.509	Feasible	
	10	1.20	Feasible	0.523	Feasible	✔
	0	1.32	Feasible	0.531	Feasible	✔
	−10	1.45	Feasible	0.540	Feasible	✔
	−30	1.79	Feasible	0.564	Feasible	✔
	−50	2.21	Feasible	0.593	Feasible	✔
Traffic	50	1.92	Feasible	0.586	Feasible	✔
	30	1.68	Feasible	0.564	Feasible	✔
	10	1.44	Feasible	0.543	Feasible	✔
	0	1.32	Feasible	0.531	Feasible	✔
	−10	1.20	Feasible	0.519	Feasible	✔
	−30	0.96	Unfeasible	0.497	Unfeasible	✔
	−50	0.66	Unfeasible	0.488	Unfeasible	✔
Construction costs	50	0.89	Unfeasible	0.363	Unfeasible	✔
	30	1.02	Feasible	0.428	Unfeasible	
	10	1.22	Feasible	0.500	Feasible	✔
	0	1.32	Feasible	0.531	Feasible	✔
	−10	1.46	Feasible	0.565	Feasible	✔
	−30	1.86	Feasible	0.631	Feasible	✔
	−50	2.54	Feasible	0.687	Feasible	✔

investigated the effect and sensitivity of those parameters via the PTV Visum 13 traffic simulation program for the case study. The simulation program was run for each critical parameter separately. After many simulations, the sensitivity of the critical parameters was obtained as shown in Fig. 8.

The sensitivity of the critical parameters is shown by means of a spider diagram for the case study. Spider diagram is a useful graph for sensitivity analysis. It presents a snapshot of the potential impact of uncertain input variables on project outcomes. Figure 8 shows potential impact of the parameters "discount rate, traffic and CC" within the range of ||±50 %||. As it is seen in the figure, the *B*/*C* rate of the project is >"1" in the range of approximate ||±30 %|| for the variation of traffic, discount rate and CC concepts in the SA. For decision making, it can be interpreted that the project is feasible, since the variation of the critical parameters produced output values >"1" for *B*/*C* rate within a range of reasonable values.

The developed FCM model was also run for the case study. The produced values depicted in Table 5 for the project were normalized within the range of ||0, 1||. After normalization, the initial vector was defined as: $A = [1\ 0.026\ 0.114\ 0.138\ 0.366\ 0.402\ 0]$. After the FCM simulation process that was accomplished in 14 iterations, the system converges to a steady state with the final vector: $A^f = [0.0102\ 0.026\ 0.114\ 0.138\ 0.366\ 0.402\ 0.531]$. The final value of the decision concept, *B*/*C* rate, $A^f(7) = 0.531$ was obtained after simulation. This means that "the project is feasible" according to the provided decision criterion in Eq. (5). The developed FCM model provides the same decision for the case study as CBA, and this means that its decision concurs with that provided by the conventional approach with SA.

In addition, the FCM model was run separately for each situation in a wide range of discount rate, traffic and construction cost concepts. Extensive simulations were conducted, and the results of the FCM model have been verified with the outcomes of the conventional *B*/*C* (see Table 6). Table 6 shows that the proposed FCM model was able to give a final decision with reasonably high accuracy. More specifically, the decision accuracy of 19 out of 21 in Table 6 was achieved for the case study. This denotes the ability of the FCM model to interpret the outcome as "feasible" or "unfeasible" for different scenarios. The traffic simulation program was run for each critical parameter in the range of (−50 +50 %) in order to assess conventional *B*/*C*. The developed FCM model was run for these parameters in the same range. The decisions of both conventional *B*/*C* and FCM model, as shown in Table 6, concur in almost all cases. Coinciding results are indicated via the sign "✔".

The developed model was also evaluated by means of MCS approach. MCS is a stochastic technique that randomly sample values from the probability distribution functions of variables in a model to compute the likely outcomes. In this study, the graph based on @Risk software is illustrated in Fig. 9. The cumulative probability curve in Fig. 9 permits an assessment of the project risk, for example by verifying whether the cumulative probability is higher or lower than a reference value that is considered to be critical. One can also assess the probability that the *B*/*C* rate will be lower than a certain value, which is adopted as the benchmark.

In the analysis, Beta-Pert distributions were used due to the inherent lack of data in CBA of highways. Triangular or Beta-Pert distributions are often used when there is no detailed information on the variable's past behavior or there is only limited sample data. In these cases, the distributions are described by a 'high value', 'low value' and 'best-guess value', which, respectively, provide the maximum, minimum and moderate values of the probability distribution with the help of experts' opinions [12]. After the simulation process, the accumulated graph illustrates the likelihood of achieving a specified *B*/*C* rate (shown on the vertical axis) or a *B*/*C* rate that exceeds that value [37]. The results of the analysis are depicted in Fig. 9, which show that there is a 96.5 % probability of having a *B*/*C* rate ≥1.152. For decision making, it can be interpreted that the project is feasible since the project risks are not high. It is observed that the final decision of MCS concurs with the final decision of the developed FCM model for the case study. In Fig. 9, the MCS also indicates that there is a 56.7 % probability of having a *B*/*C* rate equal to 1.32 (in the conventional CBA) and 0.531 (in the FCM model) for the case study. It means that the occurrence probability of the result produced by the developed FCM model for the case study is 56.7 %.

7 Discussion and Conclusion

In this study, an alternative risk model was developed to assess highway CBA. The FCM approach was used as a soft computing method to handle efficiently the effects of uncertainty and ambiguity in CBA. The concepts of CBA took part in the construction of the developed model. In addition, a RISK parameter was considered for the model. To examine the usability of the developed model, it was compared with actual feasibility studies obtained from Turkish transportation authorities. As was observed, the final decisions of the developed model concurred with the final decisions of the feasibility studies. Furthermore, a case study was conducted to further validate and substantiate the results of the developed FCM model. The case study was evaluated through SA, MCS and the FCM model. The performance accuracy of the developed model is summarized as follows: (1) the SA and the developed model were performed for the case study. The final decisions of both approaches overlapped; (2) the traffic simulation program was run separately for different scenarios of the case study. The final decisions of the conventional *B*/

C concurred with the final decisions of the developed model in almost all of the scenarios; and (3) the MCS was applied for the case study. The final decision of MCS concurred with the final decision of the developed model.

In accordance with the above results, the developed model is considered to be an alternative model for risk analysis in the highway project appraisal. Besides, some inferences about the methods used in the case study are: (1) in the conventional approach, SA gives a controversial decision, because the likelihood of occurrence of output values cannot be captured by SA. Thus, the analyst subjectively opines based on previous experience in order to provide a proper decision. Besides, performing risk analysis taking into account all the risks through SA is a time-consuming task; (2) in the MCS approach, the analysis results are based on probability distributions assigned to variables by analysts. The accuracy of probability distributions has a key role in MCS. The main weakness of MCS is the time-consuming due to the necessity of accurate distributions' definition; and (3) the developed FCM model produces comprehensible results by taking into account all the influences of uncertainty simultaneously to decision makers by means of the RISK parameter. The model generates a crisp result by analyzing the risks in the system by utilizing RISK parameter. Thus, the model directly presents the decision result (feasible or unfeasible) without the extra need of interpretation.

By way of comparisons of the developed model with the aforesaid methods, it is revealed that the FCM model is easier and more user-friendly for decision makers.

The main advantages of the proposed FCM model are: (1) its ability to cope with inherent uncertainty in the decision-making process in CBA for highways providing acceptable decisions; (2) its ease of use (user-friendly manner) for the analysts who want to assess the CBA in highway projects; (3) its low time-consuming performance; and (4) its sufficient interpretability stemming from the decision criterion defined in decision process.

To sum up, it is considered that the developed FCM model can work as an alternative model for assessing highway CBA. However, a list of limitations and assumptions has been acknowledged as: (1) the research is expert-based; (2) it mainly takes into consideration the risks in the Turkey's transportation conditions; and (3) the developed model is compared with the widely used CBA with SA and MCS by accepting their validity and reliability in highway investment assessment.

This research study is the first in the application of FCM modeling for highways CBA. Future work will be directed to the implementation of learning algorithms in parallel with expert-based methods for constructing FCM for CBA of highways and to evaluate them comparatively. A semiautomatic approach will follow for the development of the FCM model. Furthermore, the model could be improved by considering different risks with different conditions in various countries.

Appendix: Identification and Description of Risks in CBA for Highway Projects

Risk likelihood	Risk severity
AC	
1—Including missing data in the accident reports ☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	**1—The effect of this risk on the CBA** ☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
2—Including missing data in the accident statistics ☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	**2—The effect of this risk on the CBA** ☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
3—Including wrong data in the accident statistics ☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	**3—The effect of this risk on the CBA** ☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
4—Wrong determination of accident unit prices ☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	**4—The effect of this risk on the CBA** ☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
5—Changing of discount rate ☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	**5—The effect of this risk on the CBA** ☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
TV	
1—Wrong determination of unit prices of the travel time ☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	**1—The effect of this risk on the CBA** ☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
2—Wrong calculation of gaining time ☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	**2—The effect of this risk on the CBA** ☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
3—Wrong determination of time value of the load ☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	**3—The effect of this risk on the CBA** ☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
4—Wrong calculation of the existing traffic ☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	**4—The effect of this risk on the CBA** ☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high

Risk likelihood	Risk severity
5—Wrong estimation of the future traffic	**5—The effect of this risk on the CBA**
☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
6—Changing of discount rate	**6—The effect of this risk on the CBA**
☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
VOC	
1—Wrong determination of unit prices of the VOC	**1—The effect of this risk on the CBA**
☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
2—Wrong calculation of the existing traffic	**2—The effect of this risk on the CBA**
☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
3—Wrong estimation of the future traffic	**3—The effect of this risk on the CBA**
☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
4—Changing of discount rate	**4—The effect of this risk on the CBA**
☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
OMC	
1—Wrong estimation of the OMC	**1—The effect of this risk on the CBA**
☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
2—Changing of discount rate	**2—The effect of this risk on the CBA**
☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
CC	
1—Changing of unit prices of the CC	**1—The effect of this risk on the CBA**
☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
2—Changing of discount rate	**2—The effect of this risk on the CBA**
☐ Very unlikely ☐ Unlikely ☐ Medium ☐ Likely ☐ Very likely	☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high

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