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FUZZY LIFE-CYCLE ASSESSMENT APPROACH FOR QUANTIFYING ENVIRONMENTAL IMPACTS OF PAVEMENT PROJECTS UNDER UNCERTAINTY

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ABSTRACT

Sustainable development is a challenging issue which has been heavily concerned during recent decades. A considerable investment of general budget of each country is annually allocated to highway projects. Therefore, a minor improvement in this section can lead to major efficiencies in the way of sustainable development. A number of research has been conducted to evaluate the environmental effects of highway projects in a long-term horizon. Existing methods often model the projects in a deterministic approach. But considering uncertainty associated with every project compels using non-deterministic methods. While much of the basic information required for human decisions are possibilistic rather than probabilistic in nature and fuzzy set theory provides a basis for the theory of possibility. Fuzzy method as a potent tool for uncertainty-based assessment, not only covers the uncertainties, but also addresses shortcomings of probabilistic methods. In the absence of precise and complete information, fuzzy set theory is better capable of extracting and representing the required information from experts by effectively capturing their linguistic and subjective evaluations. The method presented in this paper considers the uncertainties associated with traffic demand and pavement performance by fuzzy set theory and provides a tool to compare different strategy alternatives for performing pavement project by an innovative life-cycle assessment (LCA) method. The presented LCA tool quantifies environmental effects of each construction alternative in two terms of “Global Warming” and “Energy Consumption”. Finally, the presented approach is implemented in a highway project, as a case study. The results indicate that the significant effect of pavement performance on global warming impacts and energy consumption, emphasizing that pavement performance should be taken into consideration in evaluation of different pavement construction strategies.

Keywords: Life-Cycle Assessment, Highway Projects, Fuzzy, Uncertainty, Global Warming, Energy Consumption

1. INTRODUCTION

Roadways play a vital role in societies as arteries and governments spend large amounts of budgets for construction, maintenance and development of roadways. All over the world, roadways annually tolerate more than nine thousand billion ton kilometers and passengers travel more than fifteen thousand billion kilometers among them (IRF 2010, BTS 2010). Between 20 to 40 percent of construction budget have been allocated to roadway projects in some developing countries, also notable investments have been done by private sector in roadway projects. The 7 to 9 percent allocation of annual budget to road transportation in different countries, in addition to other given reasons can decently exhibit the importance of reasonable and precise decision making about these vital infrastructures.

International agreements in confining environmental impacts especially controlling the global warming effects of industries such as Carbon Dioxide production, compelled industries to take more serious actions in environmental evaluation and impact assessment. By result, constitutions have forced industries to reduce environmental impacts like, EU countries decision for 60 percent reduction in emissions comparison to 1990s till 2050 in transportation industry (Commissie 2011). Construction industry has stepped through by using Life Cycle Assessment (LCA) as a major part of project evaluation. In fact, by the time LCA have been extended by ISO institute with presenting ISO 14040 series (ISO 1997), construction industry has used LCA for evaluating environmental impacts of projects.

Evaluating projects with a long term view have been discussed in two main categories, first the more noted life cycle cost analysis (LCCA) and second the life cycle assessment (LCA) discussed since 1990s and focused on environmental assessment of project life cycle. Subcategories can be mentioned in both groups especially in LCA, which is more immature and the lack of unity in methods and results, especially in pavement LCA, can be seen (Santero et al. 2011).

Using the standards, pavement LCA has been used in a framework of evaluating criteria like carbon dioxide (CO_2) for evaluating global warming effects, energy consumption, water pollution, air pollutions like nitro oxides (NO_x) and sulfur oxides (SO_x) and particulate matter. Among them, CO_2 is more prominent since the widespread effect of global warming. On the other hand, the variation of material production and construction methods caused to divergent and sometimes conflicting results.

The inherent uncertainty of construction activities leads to the use of non-deterministic methods in evaluations and assessments for better estimations and management especially in the early stages of project life-cycle. The high amount of uncertainty in the early phases of projects especially planning and assessment phase, makes the use of uncertain methods inevitable for better planning and management of project in all aspects including environmental burdens of project with intensive effect on public health and sustainable development. Among all methods of evaluations, Mont-Carlo simulation as a probabilistic method has been used more but the shortcomings of this method along with the considerable capability of fuzzy set theory to model the uncertain environment of the problem encouraged the researchers to use fuzzy estimations as a non-deterministic method which has simple calculations and is not so sensitive to input functions' shape (Ferson 2002).

The objective of this research is uncertain life cycle assessment of roadway's pavement project. With this objective, first the life cycle stages of roadways should be defined and the life cycle assessment of stages is then conducted. The uncertainties should be considered among life cycle assessment. In a case study the method has been used for selecting between predefined strategies and sorting them in term of environmental impacts.

2. LITERATURE REVIEW

For thorough assessment of life cycle it is first needed to understand the life cycle it self resulting to division of life cycle into stages covering the whole life. There are various naming and categorization for pavement project life-cycle stage in LCA methods, e.g. construction, operation and maintenance, final disposal and removal or reuse of materials, or manufacturing of construction materials, construction, maintenance and repair and demolition and recycling, or raw material extraction and initial transformation, manufacturing, placement, use and maintenance and removal, recycling and disposal. All researchers tried to cover the life cycle but with considering their objectives they explained some stages with more detail (Stripple and Hakan 2001, Park et al. 2003, Zapata and Gambatese 2005)

Life cycle assessment is a detailed assessment of environmental effects in all stages of a product's life cycle, however the restrictions of time, information access and resource availability obstructs the procedure. As well the previous investigations in pavement LCA can be partial life cycle assessments since not including the whole life cycle due to problems. One of the similarities is the comparison between concrete and asphalt pavements for optimizing the pavement selection under different circumstances. Although, differences can be retrieved like concentrating on special kinds of pavements or special geographical regions leading to different results (Santero 2010, Santero et al. 2011).

Three main attributes can describe a life cycle assessment including functional unit like determined length or special properties of a pavement, system boundaries exhibiting the content of details and procedures included in LCA and the third attribute is environmental criteria used in assessment like carbon dioxide (CO_2) for evaluating global warming effects, energy consumption, water pollution, air pollution etc. (Matthews and Allouche 2010).
Using different functional units is one of the main problems for following the prior research. Additionally, the differences in project properties makes the comparability in results more difficult. Hence, using prevalent specifications for functional units with subtle changes can be suggested for solving the problem. Choosing different system boundaries is also a frequent difference in previous researches. Although some life cycle stages like material extraction and production have been considered in investigations, but choosing different system boundaries is another obstacle in the way of comparing the results. Not considering the use phase as a life cycle stage can have severe effects on results since a subtle change in the large amount of use phase environmental impacts can make vast benefits or damages. It should be considered that differential effects should be assessed for the case of selecting between different alternatives since the large amount of emissions due to traffic in the whole life span of a road will cause neglecting the effects of other life cycle stages. Accurate prediction of pavement performance resulting in vehicle fuel consumption changes can be used as a right method for evaluating different alternatives. Inconsistency in environmental criteria caused by the limitations of information access or other research difficulties is another problem in prior research. Nevertheless, equivalent carbon dioxide (CO_2) can be reported as a same criterion in environmental evaluations, showing the global warming effects and having a widespread effect makes its priority higher than other criteria. (Santero 2010, Chan 2007, Egbu et al. 2009, White et al. 2010, Häkkinen and Mäkelä 1996, Treloar et al. 2004)

Among different methods for evaluating uncertainties, Mont-Carlo simulation as a probabilistic method has been used more, but the need to a large amount of calculations, sensitivity to probability distribution functions and the need of assuming relation between all inputs are some disadvantages of this method. On the other hand, Fuzzy logic may be viewed as an attempt at formalization/mechanization of two remarkable human capabilities: First, the capability to converse, reason and make rational decisions in an environment of imperfect information, and second, the capability to perform a wide variety of physical and mental tasks without any measurements and any computations (Ferson 2002, Zadeh 2008).

With reviewing literature, it is significant that a life cycle view to roadway projects with long lasting life is absolutely needed and the level of details should be sufficient considering the limitations, capabilities and objectives. In a Life-Cycle Assessment (LCA), three attributes should be considered in a way of making comparison of results more available, first the functional unit according to project properties, second the system boundaries in alliance with predefined life cycle stages and third the criteria based on information. Inherent uncertainty of construction activities in addition to lack of certainty in early stages of project especially planning and assessment of project, results using methods for managing the uncertainties with appropriate tools. Fuzzy method as a strong method which can consider the uncertainties in addition to simple calculations and inputs, can be used for better understanding of uncertainties in a quantitative manner.

3. METHODOLOGY

The life-cycle assessment (LCA) used in this research is based on three attributes, first the functional unit can be one kilometer or the whole length of roadway, second the system boundaries which is coincident with life cycle stages and level of details is based on available information and limitations and third, the equivalent CO_2 as a phenomenon for showing the global warming effect of roadways which is more global concern.

Fuzzy method is used for uncertain life cycle assessment of roadways, since fuzzy set theory presents modeling uncertainties without having precise and complete information about the conduct and distribution of parameters. A fuzzy number is not a random variable defined in probability theory, but they can present an intellectual base level and can be used as an alternative for uncertainty modeling with efficient use of expert judgment by linguistic terms (Heravi and Esmaeeli 2014). Since the inherent uncertainty of some life cycle assessment parameters, the lack of reliable information and taking account the differences between reality and estimations, fuzzy approach is selected in this study

4. ROADWAY LIFE CYCLE STAGES

As stated in Figure 1, five main stages are considered including material extraction and production, pavement construction, maintenance and rehabilitation, use and end of life. Material extraction and production stage includes extraction and production of materials needed for roadway construction and the transportation of materials. In construction stage, all construction activities and procedures like equipment needed for pavement construction and the transportation of materials are included. In maintenance and rehabilitation stage, activities like crack sealing as a preventive maintenance and mill and overlay as a rehabilitation, are considered. In use stage, the interaction of vehicles and pavement is investigated by applying life-cycle pavement performance of the project. End of life includes the demolition and disposal of old pavement and procedures related to recycling.

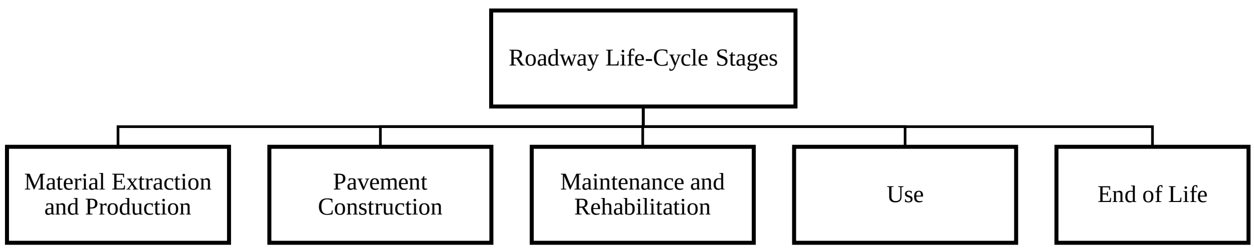

Figure 1- Roadway Life Cycle Stages

5. ROADWAY LIFE CYCLE ASSESSMENT (PAVEMENT LCA)

Previous research can lead us through a comprehensive and complete life cycle assessment by giving a complete life cycle inventory. By considering adequate stages of life cycle in environmental assessment coming from previous research and utilizing information databases and appropriate software, a proper life cycle assessment can be accomplished.

As stated in Figure 2, five main stages are considered for evaluation of environmental impacts including manufacturing, construction, maintenance, use and end of life. In manufacturing stage, the environmental effects of extraction and production of materials needed for pavement construction, is reported as material subdivision and the transportation of materials is also reported in transportation subdivision. In construction stage, the emissions and impacts of equipment needed for pavement construction are included in the equipment subgroup and the transportation of materials is separated as transportation subgroup. In maintenance stage, the impacts of material extraction and production, and equipment needed for maintenance and rehabilitation of pavement like crack sealing as a preventive maintenance and mill and overlay as a rehabilitation, are considered as material and equipment subgroup and transportation is reported in another subgroup. In use stage, the excess fuel consumption of vehicles using the road due to pavement performance and surface quality is considered and assessed. In this stage based on Pavement-Vehicle Interaction (PVI) Mechanistic model GenII developed at MIT university, the excess fuel consumption is calculated and reported in two categories as deflection and IRI. Demolition and disposal are considered in this model as end of life group in which environmental impacts of recycled material as a positive effect and emissions from equipment needed for recycling is considered in a subgroup and the transportation of materials is evaluated separately. Also some stages are excluded because of being similar in different pavement alternatives like site preparation, water management utility and infrastructures.

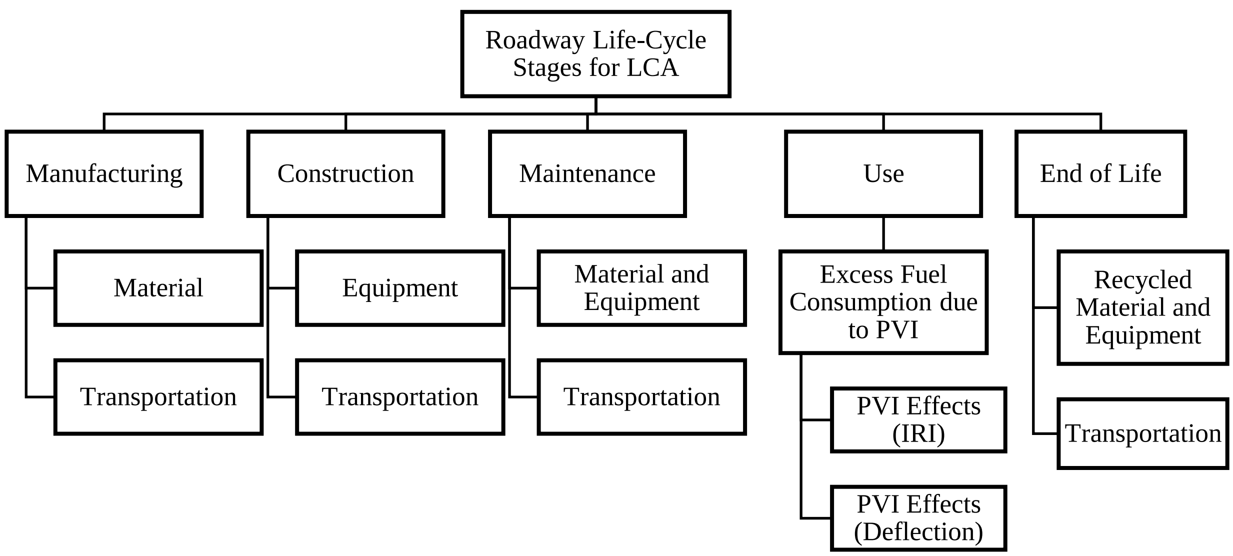

Figure 2- Roadway Life-Cycle Stages for LCA

The main criterion in this study is global warming potential stated as equivalent carbon dioxide (CO_2e) and global warming potential factors are 1 for CO_2, 25 for CH4 and 298 for N_2O (Pachauri and Reisinger 2007).

6. FUZZY LIFE CYCLE ASSESSMENT

The membership function of a fuzzy number can be defined by a complex function or by simple shapes. Because of ease of gathering the fuzzy numbers associated with uncertain input variables from experts, three types of fuzzy membership functions are used in this paper: Uniform, Triangular and Trapezoidal. These three fuzzy number along with crisp numbers can be considered special cases of the trapezoidal shape. Therefore, they can be represented by four variables; crisp=(a,a,a,a), uniform=(a,a,b,b), triangular=(a,b,b,c), and trapezoidal=(a,b,c,d). The summation of these numbers can be performed by adding the bases and peaks of the numbers (Σ first variables, Σ second variables, Σ third variables, and Σ fourth variables) (Shaheen et al. 2007). If the decision maker (DM) select a crisp number for a variable it means the amount of that variable is completely certain. On the contrast, selecting a trapezoidal number by the DM indicates even the most likely value for that variable is not certain. Therefore, a range should be selected even for the most likely values (Heravi and Esmaeeli 2014). Figure 3 shows an example of a trapezoidal number.

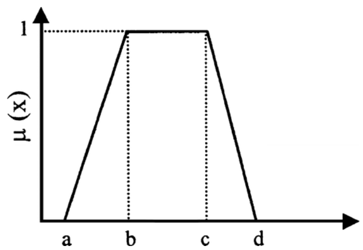

Figure 3- Four-Element Trapezoidal Fuzzy Number

For considering risk and uncertainty in fuzzy numbers, the method introduced by Fenton and Wang (2006) is used in which nine linguistic terms (from extreme pessimistic to extreme optimistic) with related triangular fuzzy numbers is mentioned. For considering decision maker's attitude in cost parameters like environmental impact, the lower the value the more desirable for decision maker, the linguistic terms and related triangular fuzzy numbers is considered in analysis according to Table 1.

Table 1-Risk Attitude Linguistic Terms and Trapezoidal Fuzzy Number

Linguistic Term	Trapezoidal Fuzzy Number
Absolutely Pessimistic	(a, d, d, d)
Very Pessimistic	(a, (b+3d)/4, (c+3d)/4, d)
Pessimistic	(a, (b+d)/2, (c+d)/2, d)
Fairly Pessimistic	(a, (3b+d)/4, (3c+d)/4, d)
Neutral	(a, b, c, d)
Fairly Optimistic	(a, (a+3b)/4, (a+3c)/4, d)
Optimistic	(a, (a+b)/2, (a+c)/2, d)
Very Optimistic	(a, (3a+b)/4 (3a+c)/4, d)
Absolutely Optimistic	(a, a, a, d)

Decision maker's confidence attitude is another type of considerations can be included in fuzzy analysis with using α-cut concept (Fenton and Wang 2006). In α-cut method, confidence attitude can be expressed by allocating a number from 0 to 1 to α (from absolutely confident to absolutely nonconfident) and using equation 1 for making the related trapezoidal fuzzy number n.

$$[1] \quad \tilde{n}^{\mathrm{LT}} = \left(a^{\mathrm{LT}}, b^{\mathrm{LT}}, c^{\mathrm{LT}}, d^{\mathrm{LT}}\right) = \left(\frac{\sum_{k=1}^{11} a_k c_k^{\mathrm{LT}}}{\sum_{k=1}^{11} c_k^{\mathrm{LT}}}, b, c, \frac{\sum_{k=1}^{11} d_k c_k^{\mathrm{LT}}}{\sum_{k=1}^{11} c_k^{\mathrm{LT}}}\right)$$

In equation 1, $a_k = a_\alpha = a + \alpha(b\text{-}a)$, $d_k = d_\alpha = d - \alpha(d\text{-}c)$, $c_k^{LT} = \mu^{LT}(\alpha)$, k=1, . . ., 9 and LT represents linguistic terms based on nine linguistic terms.

Whenever ranking and comparing of fuzzy numbers is subjected, defuzzification can be used in different methods since ranking intervals is not a straightforward process (Shaheen et al. 2007). Calculation of the expected or defuzzified value simplifies the process of ranking or comparison and different methods can be used for. In this research, the method of center of area is used for defuzzification and based on the work by Shaheen et al. (2007), the expected value and variance for trapezoidal fuzzy numbers are calculated.

7. CASE STUDY

The presented method is used for evaluating different pavement design strategies of a roadway in a case study with following specifications:

- AADT [base (design) year]: 50,000 vehicle/day, (90% light duty traffic, 10% heavy and middle duty traffic)
- Average speed: 110 km/h
- Analysis period: 35 years.

Different rigid and flexible pavements have been designed and four strategies including initial construction and maintenance and rehabilitation have been selected from technical aspect listed in Table 2 presenting activity profile of each strategy.

For calculating global warming effect of construction activities and pavement vehicle interaction for 15 kilometers of the road, Athena Pavement LCA software version 2.2.0101 (Public Release) was used and the properties like construction equipment data, material transportation data, pavement design, rehabilitation schedule and pavement vehicle interaction have been adjusted to be consistent with project circumstances.

The uncertain input variables should be considered in the used method are traffic demand and the distance for construction material transportation. Traffic demand as traffic growth rate and average distances of site to stockpile, plant to site and equipment depot to site are considered as trapezoidal fuzzy numbers like Figure 3 with a, b, c and d

Table 2- Pavement Strategy Alternatives

Alternative	Service Life (year)	Activity Type	Activity Name	Timing
No. 1	40	IC	Asphalt concrete (5.98)[a]	Base year
		RH	Thick HMA overlay (5.46)[a]	25th year
		PM	HMA crack sealing	4th, 7th, 10th, 13th, 16th, 19th, 22th, 28th, 31th, 34th, 37th year
No. 2	40	IC	Asphalt concrete (5.48)[a]	Base year
		RH	Thick HMA overlay (5.46)[a]	25th year
		PM	HMA crack sealing Thin HMA overlay	8th year 15th, 33th year
No. 3	42	IC	Jointed plain concrete (11.02)[b]	Base year
		RH	Thick HMA overlay (5.76)[a]	30th year
		PM	PCC joint cleaning & sealing HMA crack sealing	9th, 17th, 25th year 33th, 36th, 39th year
No. 4	42	IC	Jointed plain concrete (11.02)[b]	Base year
		RH	Bonded concrete overlay (10.35)[b]	30th year
		PM	PCC joint cleaning and sealing	9th, 17th, 25th, 36th year

Note: IC = initial construction; RH = rehabilitation; PM = preventive maintenance.
[a] Structural number in flexible pavement design.
[b] Layer depth in rigid pavement design (in in.).

elements described in Table 3. Three different risk attitudes (Absolutely Optimistic, Neutral and Absolutely Pessimistic) and three confidence attitudes (Absolutely Confident, Neutral and Absolutely Nonconfident) have been used for fuzzy life-cycle assessment to evaluate the variability and domain of variable changes.

Table 3- The Four Elements Considered for the Fuzzy Numbers of Average Transportation Distance and Traffic Growth Rate

Variable	a	b	C	D
Traffic Growth Rate	1.5%	2%	2%	2.5%
Average distance	10 (km)	20 (km)	30 (km)	40 (km)

8. RESULTS AND DISCUSSION

Using fuzzy life-cycle assessment for evaluating environmental effects of different pavement alternatives, results shown in Table 4 for different pavement strategy alternatives were concluded. Global warming impacts in 1000 tonnes CO_2e is measured and reported including emissions from life cycle stages described in Figure 2. Different risk and confidence attitudes were considered leading to nine different states.

Table 4 depict different alternatives in 9 states and helps to making decision between them. Alternatives number 3 and 4 (concrete pavement) have less global warming effect than the other alternatives (asphalt pavement) and perform better in this criterion. Although the good performance of this alternatives in global warming effect, other criteria especially economic and financial criterion can be more important in decision making and should be considered for a comprehensive decision.

Table 4- Global Warming Impacts of the Alternatives under Different Risk and Confidence Attitudes (1000 tonnes CO_2e)

		Confidence Attitude					
		Absolutely Confident		*Neutral*		*Absolutely Nonconfident*	
Risk Attitude	Alternative	Exp. Val.	Std. Dev.	Exp. Val.	Std. Dev.	Exp. Val.	Std. Dev.
Absolutely Optimistic	Alt. No. 1	200.57	0.81	197.60	5.56	195.77	10.52
	Alt. No. 2	302.68	0.86	301.11	9.67	298.47	21.22
	Alt. No. 3	108.05	0.37	106.99	2.37	105.78	4.60
	Alt. No. 4	108.45	0.34	107.22	2.22	106.18	4.10
Neutral	Alt. No. 1	201.15	1.00	201.39	4.87	202.47	9.15
	Alt. No. 2	303.29	1.05	306.27	8.49	309.95	18.56
	Alt. No. 3	108.31	0.45	108.53	2.08	108.77	4.00
	Alt. No. 4	108.69	0.42	108.75	1.94	108.94	3.56

Absolutely Pessimistic	Alt. No. 1	201.73	0.81	205.46	5.56	210.65	10.52
	Alt. No. 2	303.89	0.86	314.79	9.67	328.48	21.22
	Alt. No. 3	108.57	0.37	110.35	2.37	112.29	4.60
	Alt. No. 4	108.93	0.34	110.36	2.22	111.97	4.10

9. CONCLUSION

Roadways as critical infrastructures needed for development had been always noticed since the ancient times. In todays world of sustainable development, in addition to development of these essential infrastructures the sustainability of their development is also proposed as a concern. Assessment of environmental effects for preventing from environment degradation is used in the way of sustainable development. Hence, life-cycle assessment of roadways with a critical role in society development and a long life span is the main objective of this study. With review of previous research, the improvements in LCA methods despite some scarcities is tangible but, the need of uncertain methods in evaluations is completely obvious. With study of previous research, the main framework of LCA can be concluded but using uncertain methods with previous methods needs more effort. If probabilistic methods like Monte Carlo simulation are desired to be used, large amount of calculation and reliable definition of probability functions and variable relations is needed which will take large amount of time and effort.

In this research, a fuzzy life-cycle assessment approach is defined and used in a case study to clarify that with accurate use of uncertainty evaluation methods, the variability of results will be more tangible. By using the method in a case study, the compatibility of fuzzy set theory with LCA is evaluated and with considering suitable fuzzy numbers for variables results domain is investigated. One of the main advantageous of fuzzy assessment is consideration of uncertainty and reflecting the uncertainty of variables, in results without the essence of complicated computations or a large number of iterations. As can be concluded from results, different uncertain variables can be included without knowing any probability functions and the results can be explained with different risk and confidence attitudes with limited calculations. It should be pointed that allocation of membership function to different variables needs knowledge, and methods like expert judgment or regression will help to gain it.

It can be seen that with a same confidence attitude and different risk attitudes, an absolutely optimistic gives lower estimates in comparison to absolutely pessimistic. In addition, with a same risk attitude and different confidence attitudes, an absolutely confident attitude gives a narrow range of results from absolutely optimistic to absolutely pessimistic, and moving through the confidence spectrum from absolutely confident to absolutely unconfident will widen the results domain. Hence, decision maker’s confidence and risk attitude can effect the outputs of fuzzy assessment and appropriate selection of them depending on the available information and data characteristics can improve the liability and strengthen of assessment.

This research can be considered as a step toward uncertain evaluation of environmental effects in roadways. The importance of budget in projects is completely obvious thus the uncertain methods of budget evaluation is more matured. Although the importance of global warming is well declared by researchers, uncertain assessment of them is not noticed enough. The method conducted in this research can be used in different industries for evaluating the environmental effects with a simple tool with enough level of accuracy in showing the variability of results. In another word as well as we use uncertain evaluations for budgets in projects, we should evaluate the environmental effects with more accuracy and consideration of uncertainties for better management of them, since the cost of them is paid by the global community.

For future researches, the combination of life-cycle assessment and life-cycle cost analysis with fuzzy method can be useful for providing essential information for pavement alternative selection.

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