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A Novel Fuzzy-based Modeling for Route Safety Management of Hazardous Materials

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Abstract— The assessment of hazardous materials (HazMats) transport risk assumes a fundamental importance, especially in urban areas, in order to identify possible alternative routes and choose among these the route of minimum risk. It is necessary to appropriately integrate risk analysis with planning and transport management to prevent a potential danger being transformed into a real event. In this study a new application of integrated assessment model is established based on fuzzy mathematics and analytic hierarchy process (AHP). The affected area was prioritized using HazMat-Risk Area Index (HazMatRAI) then developed on the basis of Fuzzy Logic. In this regard type of Membership Function will be categorized according to Fuzzy set method in order to match the existing criteria, both solid and abstract ones. Analytic Hierarchy Process (AHP) is used to establish weighing value obtained from such assessment. Implementation of study result has much effect towards the management of disaster for the local authority, including the planning for establishment of HazMat team. Result obtained from Fuzzy Set model is HazMat-Risk Area Index (HazMatRAI) which is used to identify value of such area. The fuzzy method is capable of reducing the noise of the data by extensive training, predicting the data (after learning), and handling non-linearity. The fuzzy logic is conceptually easy to understand, flexible, tolerant of imprecise data, able to model nonlinear functions of arbitrary complexity.

Index Terms— Safety Management System, Risk Assessment, Fuzzy logic, Hazard Control, Safety Regulation, Material Handling

1 INTRODUCTION

The transport of HazMat is an important, complex, socially and environmentally sensitive problem. The preparation to handle the accident from hazardous material transportation plays an important role in the safety of such transportation that results in the loss of life, property, and environment. The major contributions of this paper are the guideline for the assessment of risk area from hazardous materials using the theory of Fuzzy Set. The assessment is conducted under the limitation of ambiguous factors in terms of both objective and subjective. Purpose of the assessment is to obtain index for the identification of risk area from hazardous materials. Thereby the risk of area that might be affected from hazardous material transportation including piping system, railing system, and road network is assessed. The result from assessment can identify level of risk of each area so that each area is able to get prepared for the prevention of accident in an appropriate manner.

General problem of engineering task is the necessity to manage uncertain data i.e. uncertainty of numbers from the measurement or experiment, and the certainty of the denotation. Fuzzy set theory is a new field of mathematical originated to handle subjective data. It is accepted that it is a theory that can handle such problem properly [4].

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The analysis for making decision regarding the area in risk of hazardous material transportation for the management of disastrous situation under the certainty and limitation to data access needs the analysis and decision making with multiple criteria.

2 MATERIALS AND METHODS

2.1 Fuzzy Set Theory

The main challenges of this study are the consideration of criteria that might make the transportation harmful, either through piping or railing system, road network, area categorization on the basis of Boolean Logic, and evaluation limitation [6]. Therefore it is required using Fuzzy Logic to solve problems that are still ambiguous or unidentified. Besides, the process used for making decision can be implemented in both quantitative and qualitative criteria and some criteria are very outstanding. The first person who introduced Fuzzy Set theory is Lofti A Zadeh, a professor of Computer of California University, Berkley. He introduced his article regarding “Fuzzy Sets” [28]. Zadeh defined fuzzy sets as sets whose elements have degrees of membership. Considered sets are viewed in a function called Membership Function. Each member of the set is represented by Membership Value which ranges between 0–1. Generally sometimes cannot be so sure that something is qualified enough to be a member of that set or not. Fuzzy set theory if more flexible as partial membership is allowed in the set, which is represented by degree or the acceptance of change from being a non-member (0) until being a complete member (1). Now fundamental idea of fuzzy set, as mentioned by Zadeh, that fuzzy set can explain mathematics is shown as follow [27]. According to the definition of fuzzy set that needs function of membership as a method to establish qualification, fuzzy set A could be represented by member x and membership degree of such value as follow (1) [28]:

$$A = \{(x, \mu A\ (x))\ \mid x \in U\} \quad (1)$$

Given that U has degree of membership for A, following symbols are used "(2)" [28]:

$$A = \int_U \mu A\ (x)/x \quad (2)$$

Fuzzy set A, in Relative Universe (U) is set from characteristic by membership function $\mu A\ :\ U\ \rightarrow\ [0, 1]$ i.e. $\mu_A\ (x)$ is value of each member x in U which identifies grade of membership of x in fuzzy set A. In this regard, fuzzy set is considered classical set or crisp set. This Membership function is called characteristic function. For classical set, there are only 2 value which are 0 and 1 i.e. 0 and 1 represents non-membership, and membership in the set respectively. The example of Fig.1 represents characteristic of Boolean set and fuzzy set. Here has shown "fuzzy set" to explain, which means the set defined in function (1) where A and B represent any fuzzy set and U represents Relative Universe (U). We found that fuzzy set is different from classical set because fuzzy set has no specific scope [17, 28].

2.2 The Risk Assessment Criteria

The risk assessment of area with the consideration of piping system, railing system, and road is a complicated process [11]. Basically there is a need to consider many aspects including location, route significance and geographical characteristics. In the past various tools for assessment was used, which can be categorized as follow:
safety, minimum travel time, minimum transportation time, population in risk, environmental quality, and geographical characteristics as shown in Table 1 [19]:

Table 1. Assessment Criteria for the Area in Risk of Hazardous Material Transportation [19]

Main-Criteria	Sub-Criteria	Membership Function	Weight	
Type of transportation in the area	Distance to transportation system if transported by road	Function I	0.045	0.062
	Distance to transportation system if transported by rail	Function I	0.013	
	Distance to transportation system if transported by pipe	Function I	0.004	
Significance of being a route for HazMat transportation	Transportation system to manufacturer / pier / industrial area is available in the area	Function II	0.027	0.040
	Number of gas station available in transportation system	Function II	0.009	
	Transportation system available in the area that reduces distance /duration of transportation	Function II	0.004	
Risk condition Of road in the area	Road characteristics that are risks of accident	Function II	0.027	0.131
	Number of accidents occurred in the past	Function II	0.020	
	Number of Hazmat transportation trucks	Function II	0.084	
Danger if accident occurs	Distance to transportation system in case of explosion / fire	Function I	0.283	0.314
	Distance to transportation system in case of leakage	Function I	0.031	
Benefits Of the area	Characteristics of urban	Function II	0.237	0.453
	Population density	Function II	0.173	
	Distance to town center	Function I	0.043	

When considered these factors, there are two topics that reflect the risk of area:

a) Risk caused by various criteria used for the assessment

b) Risk as a result from route significance

In accordance to the assessment of risk are, we divided risk scale into 5 subsets as follow "(3)" [5]:

$$R = \{R_1, R_2, R_3, R_4, R_5\} \quad (3)$$
= {most risk, much risk, risk, less risk, least risk}

All of these are hazardous materials used for model development [12]. According to the manual, it suggested that the area be restricted 100–200 meters from the scene. In case of fire, evacuate the area in the radius of 1.6 kilometers [6].

The recommended distance is used for setting up impact area. Criteria for the assessment of risk area from hazardous material transportation in terms of distance had been used to set Membership Function in this article. For example, Membership Function for distance from the scene is the function of Fuzzy Number, as shown in Fig.1 and Table 2 [19, 20].

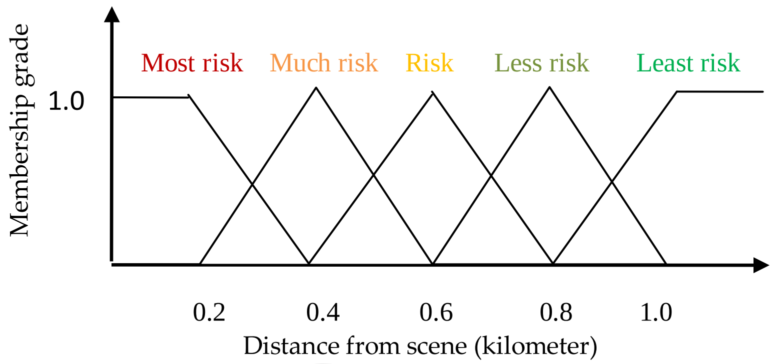

Fig.1. Sample of Membership Function: Fuzzy Number [19, 20]

Table 2. Sample of membership function for distance to transportation system in case of explosion/fire [19]

Risk Scale	Membership Function	Thresholds
Most risk	U(x) = 1 U(x) = (400-x)/200 U(x) = 0	x ≤ 200 m 200 m < x ≤ 400 m x > 400 m
Much risk	U(x) = 0 U(x) = (x-200)/200 U(x) = (600-x)/200 U(x) = 0	x ≤ 200 m 200 m < x ≤ 400 m 400 m < x ≤ 600 m x > 600 m
Risk	U(x) = 0 U(x) = (x-400)/200 U(x) = (800-x)/200 U(x) = 0	x ≤ 400 m 400 m < x ≤ 600 m 600 m < x ≤ 800 m x > 800 m
Less risk	U(x) = 0 U(x) = (x-600)/200 U(x) = (1000-x)/200 U(x) = 0	x ≤ 600 m 600 m < x ≤ 800 m 800 m < x ≤ 1000 m x > 1000 m
Least risk	U(x) = 0 U(x) = (x-800)/200 U(x) = 1	x > 800 m 800 m < x ≤ 1000 m x > 1000 m

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2.5 Membership Function II of Character

For Membership Function II of characteristics just like in Fig.2, generally it has mathematical formula as (4) [19, 20]:

$$U(X) = \begin{cases} 0 \text{ when } x = Vi \\ \quad i = 1, 2, 3, \dots m \\ 1 \text{ when } x \neq Vi \end{cases} \qquad (4)$$

Characteristic Membership Function is seen as special type of fuzzy set. Actually normal set can be used just like this. Or it can be said that when U(x) has only point 0 and 1, fuzzy set will automatically become non fuzzy set [5]. In this research, characteristic function is used for the assessment of risk area such as the area with transportation to manufacturer / pier / industrial area in the area, and amount of hazardous material being transported. However they do not indicate that there is a clear frame or it is difficult to check. Characteristic function will be used for the cases that these data is not available, and it is difficult to establish characteristic function from the assessment according to Membership Function I of Fuzzy Number. Therefore, the membership function value has only 0 or 1. Regarding danger, it can be categorized into 5 levels as usual [27]. The estimation of involved amount of each criteria that uses Membership Function II for the assessment makes us know that it can occur in 2 types which are: i) amount and risk level with direct variation and ii) amount and risk level with reverse variation, as shown in the Fig.2 [16, 27].

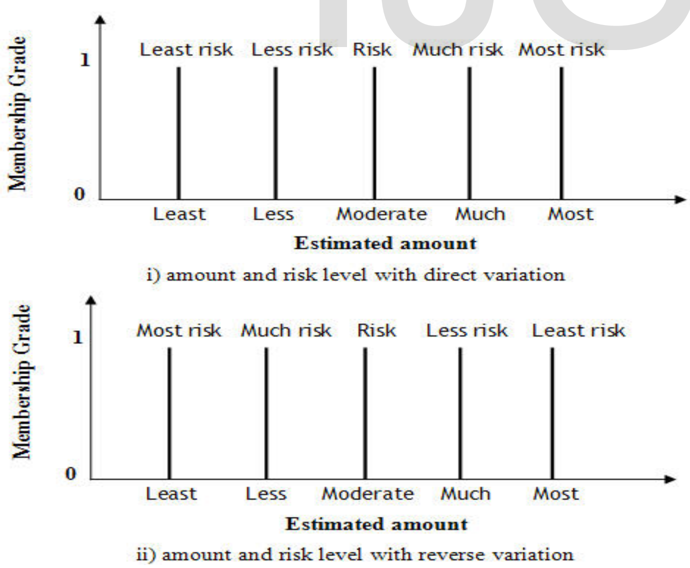

Fig.2. Sample of Characteristic Membership Function [27]

2.6 Weighting

The assessment of risk area uses Analytic Hierarchy Process (AHP) to set weight of each criterion related to the risk area. AHP is a mathematics method used for setting priority of each criterion for making decision [20]. The process consists of 3 parts which are identification and ordering, assessment and comparison of elements in order, and integration using solution algorithm of comparison result of every step [5]. Scale for the comparison of priority [14] consists of 9 levels of qualitative value: Equally Preferred, Equally to Moderately, Moderately Preferred, Moderately to Strongly, Strongly Preferred, Strongly to Very Strongly, Very Strongly Preferred, and Very Strongly to Extremely, Extremely Preferred. Quantitative value had been set from 1 to 9 respectively. Calculation result from AHP is shown in Table 1**.**

2.7 Risk Assessment Model for Areas in Risk of Hazardous Materials Transportation Developed from Fuzzy Sets

There are 14 criteria for the assessment, as shown in Table 1. Each criterion is different from each other and can be described as criteria set as follow:

$M = \{M_1, M_2 \dots Mi, Mn\}$

Where Mi; i = 1, 2, 3… n represents membership value of each risk area according to the criteria used for assessment [18].

As mentioned, each criterion has different significance which can be represented in form of sets as follow [18]:

$W = \{W_1, W_2 \dots Wi, Wn\}$

Where Wi; i = 1, 2, 3 … n represents weight of criteria used in the assessment and size of matrix is n x 1.

To divide sets for decision making for the assessment of area R, it can be done as follow [18]:

$R = \{R_1, R_2 \dots Rj, Rm\}$

Whereas Rj; j = 1, 2 .., m represents decision value of each level. Value of each risk set consists of 5 levels including 0.9, 0.7, 0.5, 0.3, and 0.1 ranging from most risk to least risk and matrix size is 1 x m.

The area to be assessed has criteria data at i-th, which can be displayed in fuzzy matrix of M as follow Fig.3 [18]:

$$M_{ij} = \begin{bmatrix} M_{11} & M_{12} & . & . & . & M_{12} \\ M_{21} & M_{22} & . & . & . & M_{2m} \\ . & . & . & . & . & . \\ . & . & . & M_{ij} & . & . \\ . & . & . & . & . & . \\ M_{n1} & M_{n} & . & . & . & M_{nm} \end{bmatrix}$$

Fig.3. Matrix m

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Matrix displaying M_{ij} shows membership value of the area to be assessed where i is in risk level j. Matrix 1 with M_{ij} is level of membership of area to be assessed of criteria i. It is a significant model of how fuzzy is represented by data used for the assessment. M_{ij} can be calculated using membership value that is related to risk level. When combined with set of weight, the assessment to find index value for the categorization of area in risk of hazardous material transportation will be using model that uses set of R and M before going to weighing of each criteria with W [12, 18].

2.8 The calculation for HazMat-Risk Area Index

HazMatRAI needs the relation of Mij through weighing using Wi on the basis of the significance of each criterion, just like Analytic Hierarchy Process (AHP) as follow (5) [20]:

$$HazMat_{RAI}=\sum_{I=1}^{N} W_i \sum_{J=1}^{M} M_{ij} R_j$$

(5)

This Fuzzy Number model was developed due to the limitation of Boolean logic. Boolean logic uses simple scope to identify risk level of an area e.g. most risk, much risk, risk, less risk, or least risk [15]. Area that has distance from transportation system less than 200 meters is considered most risk, 200–600 meters is much risk, 600 – 800 meters is risk, 800 – 1,000 meters is less risk, and more than 1,000 meters is least risk [6, 29]. When there are two areas which have distance from transportation system 395 meters and 405 meters respectively, if fire occurs, these two areas are assessed R1 (most risk) and R2 (much risk) although these two areas are close to each other. We can avoid this limitation by using membership function of Fuzzy Number. With this method, the two areas will be assessed by calculating membership function in order to obtain changes of risk in the area [29].

It can be clearly seen when using membership function i.e. the assessment of 395-meter area will be ((R1|0.025, R2|0.975, R3|0, R4|0, R5|0) and the 405-meter area will be (R1|0, R2|0.975, R3|0.025, R4|0, R5|0) instead of being assessed as two completely different areas [15, 29]. However, these two areas are considered much risk as they are in the scope of μ R2 = 0.975. This method also tell us that the 395-meter area tends to “have most risk” (R1|0.025) and it will be never be categorized as “much risk” (R3|0.025), while the 405-meter area tends to become the area with only “risk” (R3|0.025) as well. It can be clearly seen the changes of risk level when using membership function of Fuzzy Number [18, 29]. The calculation of HazMat-Risk Area Index (HazMatRAI) as mentioned above is the evaluation of every criterion for weighing. It is reliable enough to be used for the assessment of area in risk of hazardous material transportation, and it accommodates area diversity under the limitation of data access. Such index can be used to identify risk level by making comparison of the calculated values as HazMatRAI that uses comparison of related value ranging from biggest one to smallest one [8, 9].

3 RESULTS

This study has established criterions for the assessment of area in risk and it covers all land transportation, with most emphasis on road. That’s why the analysis cannot be done clearly. Using Fuzzy Set for the assessment of both objective and subjective criteria is another way to develop model in order to obtain value that can be used in the comparison of risk in the area [16]. Literature reviews and relevant researches tell us that criterions used for the assessment always emphasis on transportation by car and route network [19].

Implementation of study result has much effect towards the management of disaster for the local authority, including the planning for establishment of HazMat team. Result obtained from Fuzzy Set model is HazMat-Risk Area Index (HazMatRAI) which is used to identify value of such area. Besides it can be used for comparison of risk level ranging from biggest one to smallest one. The next step of model development is to find the value of HazMat-Risk Area Index. In this regard, many things can be done such as establishing weighing value of each criteria using various expertise to establish such weighing value. Besides, the establishment of membership level of each objective criterion can use Geographic Information System (GIS) to help categorize in order to display geographical data more clearly [29]. However, the idea of this study is to support decision making for the assessment under ambiguous context in an appropriate manner.

4 CONCLUSION

Planning for the management of disaster caused by hazardous material transportation needs to pay much attention to transportation system. Transportation by road has more risk of accident than other systems; however facts about areas in risk of hazardous material transportation are rare and difficult to access. The fuzzy method is capable of reducing the noise of the data by extensive training, predicting the data (after learning), and handling non-linearity. The fuzzy logic is conceptually easy to understand, flexible, tolerant of imprecise data, able to model nonlinear functions of arbitrary complexity, able to build on the experience of experts, and based on natural knowledge.

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