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Risk Assessment for Hazardous Materials Transportation

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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 the present study, we introduce a new decision model, calibrating weights for each choice criterion, for different stakeholders. A comparison with the approach of a different model proposed by the author (Leonardi, 2008) is presented.
Keywords: *HazMat, route optimization, risk analysis, decision support, multicriteria decision analysis.*

1 Introduction

The transport of HazMat is an important, complex, socially and environmentally sensitive problem; involving a plethora of parameters: economic, social and environmental (figure 1). Generally HazMats have to be transported from a point of origin to one or more destination points. The origin points are fixed facilities where the HazMats are produced, or stored. The HazMats are then transported from a production facility to storage, distribution, or another facility where the HazMat is required.

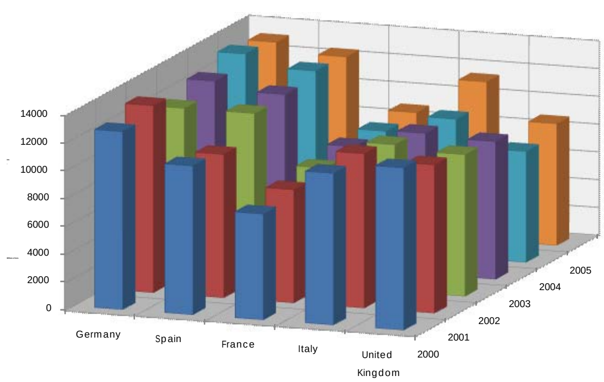

Figure 1 - Dangerous goods transported by road in Europe.

Typically, the transporter will wish to use the minimum cost route. It is also being required that the route(s) taken are to be chosen so as to minimise exposure to hazard in the event of an accident.

2 Risk Analysis In Hazmats Transport

The problem that arises when transporting HazMat is how to select a route where economic and risk issues are considered.

On the one hand HazMat transport has to be economically feasible for the stakeholders directly involved in this activity. On the other hand, HazMat transport must pursue safe transport by minimizing risk throughout the whole transportation process.

In the planning of routes, in order to identify the route of minimal risk between O and D, it is necessary to identify the "risk factors" (hazard, vulnerability and exposure) which must be considered to achieve the objective. Risk can be defined as the expected consequences associated with a given activity. Considering an activity with only one event with potential consequences risk R is thus the probability that this event will occur (accident) P multiplied by the consequences given the event occurs C.

$$R = P \cdot C \tag{1}$$

For an activity with n events the risk is defined by:

$$R = \sum (P_i \cdot C_i)$$

where P_i and C_i are the probability and consequence of event i.

Or more generally we have:

$$R = \sum (P_i \cdot C_i^{\alpha})$$

where α is a weight factor of consequences (depending on social perception of gravity of the consequences).

Equation (1) can also be written as:

$$R = P \cdot V \cdot N$$

where C is defined as: $C = V \cdot N$

V is the vulnerability, defined as the resistance of people, infrastructures, buildings and goods when the emergency occurs.

N is the exposure, that can be defined as the elements (people, goods and infrastructures) affected during and after the event.

Considering equation (1) two types of measure for risk reduction may be defined:

1) prevention, which consists of reducing the level of P;
2) protection, which consists of reducing the level of M.

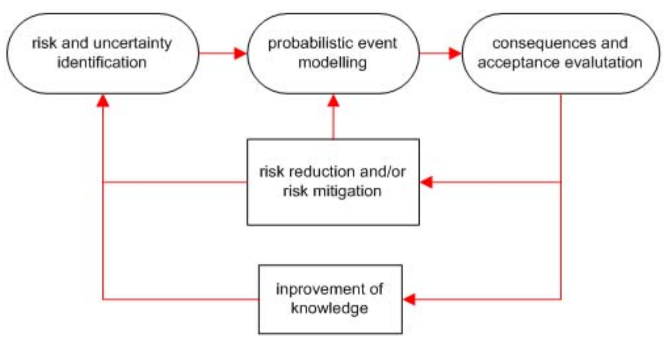

Figure 2 - Principal flow diagram of risk assessment.

The so estimated value of risk R may be considered in an absolute sense or to represent a term of comparison between different alternatives and to evaluate if the risk is more or less tolerable or to compare different solutions, assuming in analyzed road network various routes linking the two set points and assessing the value of risk for each.

3 Route Planning For Hazmats Transport

In the process of route optimization for the transport of dangerous goods a cost-benefit analysis that does not take into account the impact that a possible accident could have on biotic and abiotic components of the concerned territory is not sufficient.

These impacts are associated with pollution effects on people and the environment, resulting from the emission of pollutants around a vehicle involved in an accident. This polluting activity is very complex and stochastic, governed to a large extent by the meteorological conditions (mainly winds) prevailing at the time and site of the accident. The affected area in this case is relatively large. As a consequence, the quantification and evaluation of related costs is a difficult problem not yet satisfactorily resolved.

In recent years, several route optimization models for HazMat transport have been proposed, but there is still scope for improvement in the development of a route optimization model for HazMat transport. The proposed methodology will be shaped in such a way as to deal with the issue of integrating different risk sources, taking into account different hazards, and different elements at risk with their respective vulnerability. In this paper factors related to economic issues will be considered in order to ensure the economic sustainability of transport operations; also factors related to risk issues will be dealt with. For risk issues man-made and natural hazards will be considered, as well as population and buildings will be considered as elements at risk.

In particular, in this paper the problems relating to the transport of HazMat by road are analyzed, focusing the attention on possible problems related to the crossing of urban areas with a high rate of human presence.

The literature dealing with the problem of routing hazardous materials is rich and numerous models have been proposed in recent years.

Robbins (1983) proposed three models having as objectives respectively:

1) the minimisation of the size of the population affected by the accident;

2) the minimisation of the route length.

Saccomanno and Chan (1985) proposed a model that could represent more realistically the effects of an accident on the surrounding population. Actually, the model employs two criteria: a minimum risk criterion and a minimum accident likelihood. A third criterion dealing with the economics of the problem, that of minimization of the truck operation cost, is also involved.

Zografos and Davis (1989) developed a multi-objective decision making model. The four objectives proposed to consider in the model are:

(a) population risk; (b) property damages; (c) truck operation cost; (d) equitable distribution of risk by imposing capacity limits on the network links.

Karkazis and Boffey (1994) selected the routes to minimize the expected damage effects on the population in case of an accident. The model proposed generalizes the existing one in the following aspects: (1) the dispersion of pollutants is determined by the meteorological conditions; (2) the population can be distributed arbitrarily and anywhere on the plane.

Leonelli et al. (2000) developed a route optimization model using mathematical programming to calculate the optimal routes. The optimization problem is presented as a single objective minimum cost-flow problem, where the objective is to minimize the total cost over the route.

To avoid the increase of uncertainty in calculation of optimal route for HazMat transport, Bonvicini et al. (1998) proposed in their research study the reduction of the uncertainty in the estimation of the probability values later to be used in the calculation of individual and societal risk by means of fuzzy logic.

Frank et al. (2000) developed a spatial decision support system (SDSS) for route selection for HazMat transport. A user interface for the model was developed using a GIS environment for the visualization of optimal routes, while in the model mathematical programming was used for the estimation of optimal routes. The model aims to minimize the travel time between the origin and destination points, but the objective is subject to a set of constraints. The distance travelled, the accident probability on the route, the population exposed, and the risk for the population define the constraint functions of the model. The risk for the population is defined as the accident probability of a network section multiplied by the number of persons attributed to the same network section.

Zografos and Androutsopoulos (2004) developed a model that seeks to achieve the lowest level of operational costs and the highest level of safety while transporting HazMat. The optimization problem is presented as a bi-objective routing and scheduling problem. The two objectives are the minimization of operational costs and the minimization of the risk for the population. To solve the bi-objective mathematical problem the weighting method is proposed.

3.1 The proposed methodology

The proposed model estimates the risk of each route among those identified and chooses the route with minimal risk based on a set of criteria (goals) and their weights.

Risk analysis of different alternatives to achieve the elimination of unacceptable alternatives and to find the route with minimal risk through Multi-Criteria Analysis (MCA).

The solutions to these problems can concern both the creation of the best alternative and the choice of the most satisfactory alternative within a default set of alternatives.

Since, in this case, the choiceis limited to a finite and discrete number of alternative routes, the model refers to the multi-attribute.

Once the choice set is defined, it is necessary to choose the assessment criteria in function of the objectives to be pursued and, consequently, the indicators for measuring the performance of different alternatives.

So the MADM (Multi Attribute Decision Making) problem can be represented by a valuation matrix:

alternative path k

	criterion 1	$\cdots$	criterion m
Alt 1	$x_1(1)$	$\cdots$	$x_1(m)$
$\vdots$	$\cdots$	$\cdots$	$\cdots$
Alt k	$x_k(1)$	$\cdots$	$x_k(m)$

performance alternative k
with respect to attribute m

The objectives that will be used as criteria in the route optimization model presented in this study are (Castillo, 2004 and Leonardi, 2008):

1) minimization of travel time,
2) minimization of travel distance,
3) minimization of risk for the population,
4) minimization of risk for the urban environment,
5) and minimization of risk related to a natural hazard.

The objectives are not fixed; they reflect the interests of the stakeholders involved in the decision-making process. However, in order to give an understandable explanation of the proposed method, each of these objectives will be described below:

a) minimization of travel time and minimization of travel distance.

In order to reduce costs, private or public companies in charge of HazMat transportation often use the shortest routes available.

The shortest route available can be identified as the route with the lowest travel distance and/or travel time (Zografos and Davis: 1989; Leonelli, Bonvicini et al.: 2000; Fabiano, Curro et al.: 2002). The travel distance is simply the length of each arc. The total travel distance is the sum of length values of every arc in the route.

$$d_{route} = \sum_{arc \in route} l_{arc}$$

l_{arc} = length of each arc.

The travel time for each arc can be estimated by dividing the length of the arc by the arc average speed. Impedance time values can be added to represent average waiting time at road intersections. The route travel time will be:

$$t_{route} = \sum_{arc \in route} [(l_{arc} \times \overline{v}_{arc}) + t_{arc}]$$

where: $\overline{v}$ = average speed for each arc;

t_{arc} =average waiting time at arc intersection.

b) minimization of risk for the population

According to Zografos and Androutsopoulos (2004), the risk for the population in relation to a HazMat transport accident is defined as the product of the probability of the HazMat transport accident and the exposed population.

The probability of the HazMat transport accident is proportional to the accident rate over the transport network and the probability of the HazMat transport unit being involved in an accident.

$$ap_{arc} = ar_{arc} \times hp$$

where:

ap_{arc} = accident probability on each arc involving a HazMat transport;

ar_{arc} = accident rate for each arc in the transport network;

hp = probability for HazMat transport unit to be involve in an accident.

The population exposed to the hazard is the sum of the on-route and off-route population.

$$p(ex)_{arc} = p_{on} + p_{off}$$

The first is the population estimated to be travelling on the arcs that could be affected by the accident; this is the number of vehicles on the arc multiplied by the average number of persons per vehicle. The latter is the population situated within the impact area of the accident:

$$p(ex)_{arc} = \left(n_{vehicles} \times n_{\frac{persons}{vehicle}}\right)_{arc} + pop_{arc}$$

where:

$p(ex)_{arc}$ = number of persons exposed to an accident event along one arc;

p_{on} & p_{off} = estimated population on and off-route for each arc;

$n_{vehicles}$ = average number of vehicles travelling on one arc;

$n_{\frac{persons}{vehicle}}$ = average number of persons per vehicle;

pop = number of persons situated within the impact area of the accident site.

The risk of the route will be given by the summation of the risk values of every arc in the route. This risk measure will indicate the number of persons expected to be injured or to die in case of a HazMat accident occuring:

$$Rpop_{route} = \sum_{arc \in route} \left(ar_{arc} \times hp \times p\left(ex\right)_{arc} \right)$$

c) minimization of risk for the urban environment

The probability of fire occuring once a HazMat transport accident has taken place can be estimated by multiplying the fire probability and the probability of a HazMat transport accident (which has been already defined in the previous phase).

To estimate building vulnerability in case of fire, the predominant building material type per arc is considered. For areas with a predominant type of building material of reinforced concrete, a low building vulnerability value will be assigned, whereas the areas where wood is the predominant building material type will have a higher building vulnerability assigned. The specific risk for the urban environment will be the result of multiplying HazMat accident probability, fire probability, and estimated building vulnerability in relation to fire:

$$Rurb_{route} = \sum_{arc \in route} \left(ar_{arc} \times hp \times fp \right) \times bv_{arc}$$

where:

$Rurb_{route}$ = relative risk value estimated to represent the degree of urban damage along the route produced in case of fire triggered by HazMat transport accident;

fp = fire probability;

bv_{arc} = bulding vulnerability in relation to fire assigned to each arc.

d) minimization of risk related to a natural hazard

If HazMats are being transported through a city, route selection should also consider building vulnerability to the natural hazard.

For example in the case of earthquake, the amount of debris produced by the collapse of buildings during the earthquake event increases the hazard of an accident occuring.

The value assigned to each arc can be labelled as earthquake-building risk score, making reference to the fact that the natural hazard considered is related to an earthquake and the vulnerability is based on buildings. The route optimization equation will then be:

$$Rb_{route} = \sum_{arc \in route} Rb_{arc}$$

where:

Rb_{route} = qualitative risk measure of the amount of expected building damage in case of an earthquake along the route;

Rb_{arc} = earthquake-building specific risk score assigned to each arc.

3.2 Construction of an evaluation matrix

Now we have to define an opportune scale of measure upon which to measure the relative importance of each considered criterion (objectives). The methodology used is based on a complete comparison of the elements taken two at a time (a total of $m(m-1)/2$ comparisons for m elements).

Suppose that a decision-maker wishes to elicit the relative priorities, or weights of importance, of m entities, then he has to compare them two at a time and make a simple binary choice, selecting the objective more important between the two ones considered and after to assign a value between 1 to 9.

So it is possible to write the pairwise comparison matrix $[P]$(square, reciprocal and positive) of dimension $m \times m$, whose elements p_{ij}, said coefficients of dominance, define the relative importance of the attribute (i) with respect to the attribute (j) and have the following properties:

$$\begin{aligned} p_{ij} &> 0 \qquad & p_{ij} \times p_{jk} = p_{ik} \\ p_{ii} &= 1 \qquad & p_{ji} = \frac{1}{p_{ij}} \qquad \forall i \end{aligned}$$

$$P = \begin{matrix} P_{11} & \cdots & P_{1m} \\ \vdots & \ddots & \vdots \\ P_{m1} & \cdots & P_{mm} \end{matrix}$$

Importance Value	Definition
1	Equal importance
3	Weak importance of an objective over another
5	Strong importance of an objective over another
7	Demonstrated importance of an objective over another
9	Absolute domination of an objective over another
2, 4, 6, 8	Intermediate values between the two adjacent

The matrix $[P]$ can be also represented in function of the weights $w_1, w_2, \ldots, w_m$ of the single elements, determining the coefficient of dominance of every couple as the ratio of the respective weights, that is: $p_{ij} = w_i/w_j$

$$P = \begin{matrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_m \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_m \\ \vdots & \vdots & \vdots & \vdots \\ w_m/w_1 & w_m/w_1 & \cdots & w_m/w_m \end{matrix} \tag{2}$$

Therefore, it is easy to prove that the following matrix relation is verified:

$$[P] \times \overline{W} = m \times \overline{W} \tag{3}$$

where:

$$\overline{W} = [w_1 \quad w_2 \quad \cdots \quad w_m]^T$$

Note that the matrix $[P]$ is a consistent one, or it satisfies the condition $p_{ij} = p_{ik} \cdot p_{kj}$ for all the values of i, j, k.

The relationship (3) expresses algebraically the fact that is an eigenvector of $[P]$ with eigenvalue m.

It is not possible to determine the values p_{ij} as w_i/w_j, in fact wi and wj are unknown. To evaluate the "weight" of a set of attributes it is necessary to rely on the judgements of one or more experts. Not having measuring instruments but only his personal experience, the expert is not able to determine directly the weights w, but he can only give some approximate valuations of their ratio with the aid of the semantic scale or with the rating technique. Therefore, the matrix $[P]$ given by the expert decision-maker, in the majority of cases, is not consistent. In this case, to determine the weights w it is necessary to make some simple considerations.

- If $\lambda_1, \lambda_2, \ldots, \lambda_m$ are m numbers that satisfy the equation:

$$[P] \cdot x = \lambda \cdot x \tag{4}$$

(that is, they are the eigenvalues of $[P]$) and if for every values of i is $p_{ii} = 1$, then:

$$\sum \lambda_i = m \qquad\qquad i = 1, ..., m \tag{5}$$

- If (3) is valid, all the eigenvalues are necessarily equal to zero except one, that is equal to m. According to this, when $[P]$ is a consistent matrix m is its maximum eigenvalue (or right principal eigenvalue) and it is the only one to be different from zero.

- If the values of p_{ij} of a reciprocal and positive matrix are slightly modified, the corresponding values of the eigenvectors change a little, slightly and in a continuous way.

Combining the preceding results we can deduce that when the elements of the principal diagonal of the matrix $[P]$ are all equal to 1 and the matrix is consistent, shifting slightly the values p_{ij} the principal eigenvalue λ_{max} of the matrix assumes a value that doesn't change much from m, while the residual eigenvalues stay near to zero. Then, to resolve the problem it will be sufficient to determine the vector that satisfies equation:

$$[P] \times \overline{W} = \lambda_{max} \cdot \overline{W} \tag{6}$$

in other words it will be sufficient to determine the principal eigenvector corresponding to the eigenvalue λ_{max} of the matrix $[P]$.

There is still the problem of establishing if the weights that are obtained with (6) represent the view of those who made the pairwise comparisons. In other terms it is necessary to establish if and in what measure the values of the fractions w_i/w_j, calculated after having determined the principal eigenvector, are different from the estimate values pij given by the expert. To this aim we define an index of consistence (CI, consistency index) and a percentage of consistence (CR, consistency ratio), that allow us to measure the difference between these two set of values:

$$CI = \frac{\lambda_{max} - m}{m - 1} \tag{7}$$

$$CR = CI \times RCI \tag{8}$$

where the index RCI(random consistency index) is calculated making the average of the CI of numerous mutual matrixes of the same order, whose coefficients are randomly produced by a computer. The different values of RCI in function of m are proposed in the following table:

m	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RCI	0.0	0.0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

It is evident that in the case of perfect consistence CI is equal to 0, in fact, when the matrix is perfectly consistent (6) coincides with (3) and the principal eigenvalue λ_{max} is equal to m. If the value of the CR index is smaller than 0.1 the matrix $[P]$ compiled by the expert is acceptable, if $CR > 0.1$ the difference from the condition of perfect consistence is judged unacceptable, in this case the expert has to try hard to increase the coherence of his judgments modifying, totally or in part, the values p_{ij}.

Once determined the vector of the weights can be normalized so we have:

$$\sum_{j=1}^{m} w_j = 1$$

For a comparison of alternatives, the different performances, assessed in function of the criteria considered, must be appropriately normalized:

$$r_i = \frac{x_i\,(j)}{\sum\limits_{column\ j} x_i\,(j)}$$

so we have the following normalized evaluation matrix:

	criterion 1	**…**	**criterion *m***
	w_1	…	w_m
Alt 1	$r_1(1)$	…	$r_m(1)$
…	…	…	…
Alt *k*	$r_k(1)$	…	$r_m(k)$

The performance of each alternative k is represented by the weighted sum of its individual performance.

$$v\,(k) = (r_1\,(k))^{-w_1} + \cdots + (r_m\,(k))^{-w_m} \tag{9}$$

In (9) the weights are introduced as negative exponent.

So, it is possible to sort the global performance of alternatives finding the one with minimum risk.

The best alternative, denoted with A^* , can be determined as:

$$A^* = \arg\left\{\max_{a\in A}(v_i)\right\}$$

3.3 Example

The proposed methodology has been applied to a simple case of route planning, where the considered criteria are those illustrated above, we have 5 criteria and 5 alternative routes:

	C1	*C2*	*C3*	*C4*	*C5*
A1	10	110	1005	0,32	0,15
A2	15	120	1404	0,40	0,37
A3	18	90	1233	0,23	0,21
A4	23	87	1786	0,52	0,40
A5	21	94	892	0,39	0,31

Normalized matrix:

	C1	C2	C3	C4	C5
w	0,1	0,2	0,4	0,1	0,2
A1	0.11	0.22	0.16	0.17	0.10
A2	0.17	0.24	0.22	0.22	0.26
A3	0.21	0.18	0.20	0.12	0.15
A4	0.26	0.17	0.28	0.28	0.28
A5	0.24	0.19	0.14	0.21	0.22

Weighted matrix:

	C1	C2	C3	C4	C5	v
A1	1,242	1,354	2,087	1,192	1,572	**7,447**
A2	1,192	1,331	1,825	1,166	1,312	**6,827**
A3	1,171	1,410	1,923	1,232	1,470	**7,205**
A4	1,142	1,419	1,658	1,136	1,292	**6,647**
A5	1,153	1,397	2,188	1,169	1,360	**7,267**

The best alternative is $A1$.

3.4 CONCLUSIONS

The paper illustrates a methodology that integrates different risk and economic factors in a route optimization problem for HazMats transport.

In order to be able to evaluate routes a Multiple-Attribute approach was proposed.

The model proposed concurs to determine an ordering of the different solutions giving a concrete tool to support decisions (DSS).

In this approach we have wanted to do a major importance at the weights of the considered criteria. Also, the model can be easily customized to other case studies and adapted to different routing problems.

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