ROUTES PLANNING FOR HAZMAT TRANSPORT

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ABSTRACT. The risk analysis assumes a fundamental importance in the transport of dangerous goods, especially in urban areas, in order to identify possible alternative path and choose among these the path of minimum risk.
It is necessary to appropriately integrate risk analysis with planning and transport management to prevent that a potential danger can be transformed into a real event.
However, the choice of the optimal route, where this is both in terms of economy and safety is not an easily achievable goal, which in practical applications reveals to be a major concern, considering the different stakeholders directly or indirectly involved in decision making. In the present study, a methodological approach for the characterization of the routes, to be placed behind a system of decision support (DSS) for identifying the minimum risk routes, is proposed.

Keywords: *HazMat, route optimization, risk analysis, decision support.*

INTRODUCTION

One of the major risks associated with the development of our industrial society is represented by the processes of production, distribution and storage of materials that, in case of accidental dispersion, can cause damage to the environment and to human beings. The use of these types of materials certainly generates economic benefits; nevertheless the term "hazardous" is an indicative that negative and damaging consequences can result from an accidental event, which takes place in activities where hazardous materials are present. If such event occurs, the consequences can affect our society and the environment. In most cases, the attention is directed exclusively at the risk relating to the production of dangerous goods (HazMat) and, therefore, to industrial plants, and often the risk associated with transportation is neglected.

In recent years, the quantity of dangerous goods transported by road in Europe has remained constant at high values and in some countries, like Italy, has increased considerably. In Italy in 2005 77.774.537 tons of hazardous goods were transported by road, for a total of 11.870 million tons-km. In 2004 73.377.960 tons of hazardous goods were transported by road, for a total of 10.384 million tons-km, with an increase of 14.3% [Ministero dei Trasporti (2005)]. The countries in which the largest quantity of dangerous goods transits are: Germany (13.158 million tons-km), Spain (12.474 million tons-km) and Italy (11.870 million tons-km). Of course, for a right comparison of data, such amounts must be related on the size of territory, population or the industrial production of each State.

The transport of HazMat is an important, complex, socially and environmentally sensitive problem; involving a plethora of parameters: economic, social and environmental. 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 HazMat are produced, or stored. The HazMats are then transported from a production facility to storage, distribution, or another facility where the HazMat is required.

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 to minimise the exposure to the hazard in the event of an accident. In most cases [Karkazis and Boffey (1995)], "*risk*" and safety interests conflict with economic interests, making the decision-making process a complex task. The problem that arises when transporting HazMat is how to select a route where economic and risk issues are considered. On one hand the HazMat transport has to be economically feasible for the stakeholders directly involved in this activity. On the other hand, the HazMat transport must pursue the safe transport by minimizing the risk throughout the whole transportation process.

RISK PREVENTION IN THE TRANSPORT OF DANGEROUS GOODS

In the process of routes 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 the 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. Several models of dispersion of pollutants which allow to estimate the level of concentration in the considered areas, depending on the particular weather conditions, have been proposed.

A first attempt was made employing the classic Gaussian plume dispersion model. Further developments of Gaussian model were made by Karkazis and Boffey (1994) and Cafiso and Colombrita (2001).

In particular, it is possible to distinguish two types of effect from an accident involving vehicles transporting hazardous materials:

a) Injuries to people and physical damage as a result of the shock of an explosion associated with an accident. The severity of these effects is inversely proportional to the distance from the site of the explosion, and in general these effects are not influenced by the prevailing meteorological conditions. The resulting damage is confined to a circle centred at the site of the explosion and having a radius of a few hundred meters (in the more serious incidents).
b) Contamination of humans and the environment resulting from the emission of pollution that can be carried by the wind many kilometres. The resulting effects can be considerably widespread and depend both on the meteorological conditions at the time of the accident and the distribution of population around it.

It is obvious that the effects of an explosion, as opposed to low emission effects, are directly felt by the people (society). As a consequence, the vicinity of a route along which hazardous materials are transported to an urban site creates serious social problems for the people living there, mainly associated with the anxiety caused by the expectancy of an accident. In the decisional process therefore, it is fundamental a forecasting analysis of the risk, given by the product of the probability that the dangerous event happens, a nd the magnitude of its consequences. A forecast for the risk scenario allows to assess the damage caused by the accident, in terms of social and environmental costs, so to take actions to minimize these costs.

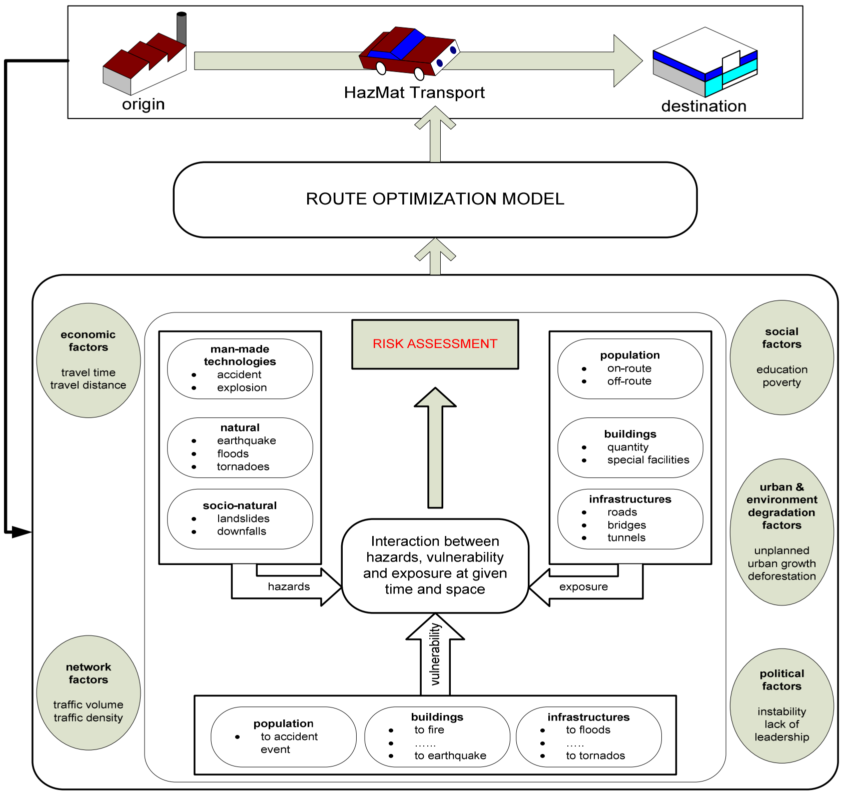

Figure 1 - Operative plan of route optimization model [Castillo (2004)].

ROUTE OPTIMIZATION FOR HAZARDOUS MATERIALS TRANSPORT

In the planning of routes, in order to identify the path to minimal risk between O and D, it is necessary to identify the "risk factors" (hazard, vulnerability and exposure) which is necessary to consider to achieve the objective.

In the last years, several route optimization models for HazMat transport have been developed, but there is still a 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 assure the economic sustainability of the transport operations; also factors related to risk issues will be dealt. For the 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.

Literature review

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

To solve this multi-objective optimization problem, the authors proposed using goal programming for the following reasons: it offers considerable flexibility to the decision-maker and allows the creation of many scenarios, it does not require the conversion of all objectives to a single monetary value when evaluating different scenarios, and, most important, it requires only a limited amount of information for the decision-maker.

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. The total cost over the route is the summation of the cost values assigned to every transport network section that is part of the route. The cost, in this case, results from the addition of the "truck operating costs" (out-of-pocket) and "risk-related costs". The "out-of-pocket" costs represent the operational costs related directly to the transport activity, whereas the 'risk-related' costs are related to the expected number of persons affected in case of the occurrence of an accident involving a HazMat transport unit. The risk-related costs in monetary terms are given by the product of Human Life Value HLV and the "yearly expected number of fatalities". 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 the route selection for HazMat transport. A user interface for the model was developed using a GIS environment for the visualization of the optimal routes, while in the model mathematical programming was used for the estimation of optimal routes. The model aims to minimizing the travel time between the origin and destination points, but the objective is subject to a set of constraints. The travelled distance, the accident probability on the route, the population exposed, and the risk for the population define the constraints 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.

The proposed routing model

The proposed model is articulated in two principal phases:

1. *Selecting a set of admissible routes economical acceptable:*
   Selecting, through Penalty Iterative Method (IPM), a set of paths characterized by minors travel times, to ensure the economic efficiency of transport, and by some spatial difference of alternatives to distribute the risk territorially. The IPM is a suitable algorithm to generate a large set of alternative paths. It is based on a repetitive application of an appropriate shortest path algorithm. After each application of the algorithm, a cumulative penalty on the impedance of all links in the resulting shortest path is imposed.
   Hence, the repeated selection of the same set of links is discouraged and dissimilar paths may be generated as results [Bonvicini *et al.* (1998)]. The problem of finding a set of spatially dissimilar paths between an origin and a destination can be achieved by using other methods like: the Gateway Shortest Paths (GPS) proposed by Lombard and Church (1999), based on a constrained shortest path problem and the Minimax Method proposed by Kuby *et al*. (1997), it aims to generate a set of dissimilar paths by selecting a sub set of a large set of paths.
2. *Estimating the risk of each route between those identified and choice of route with minimal risk based on a set of criteria (goals) and their weights:*
   Risk analysis of different alternatives to achieve the elimination of alternatives not acceptable and to find the path with minimal risk through the Multi-Criteria Analysis (MCA).
   All the multi-criteria problems has some common characteristics, which can be listed in the followings points:
   - objectives/attributes are multiple, the decision-making has to define objectives and/or remarkable attributes to analyse the problem;
   - conflicts among the criteria, the criteria are clashing among them;

- measure units are incommensurable, every objective and/or attribute is measured using different units [Leonardi (2001)].

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

To focus the problem there are, therefore, two possible set of alternatives: one contains a finite number of alternatives, while the other contains an endless number of them. Then it is possible to divide in two categories the multi-criteria problems, on the base of the number of alternatives. A finite number of alternatives concern the multi-attribute problems, an endless number of alternatives concern the multi-objective problems.

The multi-objective analysis can be associated to problems that have a set of alternatives not predetermined. Therefore, it has solution of continuous type, where more objectives are pursued contemporarily.

The multi-attribute analysis is associated to problems that have a finished number of predetermined alternatives. To each alternative is associated a level of satisfaction of the attributes (not necessarily quantifiable) on the base of which the final decision is assumed. The problem concerns the selection of the alternative, not its creation.

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

Once the choice set is defined, it is necessary to choose the assessment criteria in function of 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 generated by IPM

	Alt 1	$\cdots$	Alt k
criterion 1	$g_1(1)$	$\cdots$	$g_1(k)$
$\vdots$	$\cdots$	$\cdots$	$\cdots$
criterion m	$g_m(1)$	$\cdots$	$g_m(k)$

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: *minimization of travel time, minimization of travel distance, minimization of risk for the population, minimization of risk for the urban environment, and minimization of risk related to a natural hazard* [Castillo (2004)].

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 in the following:

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

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

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

where: 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:

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

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 to be involved in an accident.

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

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.

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

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:

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

where: $p(ex)_{\mathrm{arc}}$ = 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;
$n_{\frac{\mathrm{persons}}{\mathrm{vehicle}}}$ = 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 dead in case of a HazMat accident to occur:

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

c) minimization of risk for the urban environment

The probability of fire to occur 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 the 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 the HazMat accident probability, the fire probability, and the estimated building vulnerability in relation to fire:

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

where: $Rurb_{\mathrm{route}}$ = 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 the HazMats are being transported through a city, the route selection should also consider the building vulnerability to the natural hazard.

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

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 be then:

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

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.

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 used methodology 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) respect to the attribute (j) and have the following properties:

$$p_{ij} > 0 \qquad p_{ij} \times p_{jk} = p_{ik}$$
$$p_{ii} = 1, \qquad p_{ji} = \frac{1}{p_{ij}} \qquad \forall i$$

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

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: $p_{ij} = w_i/w_j$

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

$$[\mathbf{P}] \times \overrightarrow{\mathbf{W}} = m \cdot \overrightarrow{\mathbf{W}} \qquad (1)$$

where: $\overrightarrow{\mathbf{W}} = \begin{bmatrix} w_1 & w_2 & \cdots & w_m \end{bmatrix}^T$,

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 (1) expresses algebraically the fact that $\overrightarrow{W}$ 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 w_i and w_j 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 measure instrument 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 the cases, is not consistent. In this case, to determine the weights w it is necessary to make some simple considerations.

- If λ_1, λ_2, …., λ_m are m numbers that satisfy the equation:

$$[\mathbf{P}]\cdot \boldsymbol{x} = \lambda \cdot \boldsymbol{x} \qquad (2)$$

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

$$\sum \lambda_i = m \qquad (i = 1,.....,m) \qquad (3)$$

- If (1) 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 his 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 correspondent values of the eigenvectors change a little, slightly and in 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 next to zero. Then, to resolve the problem it will be sufficient to determine the vector that satisfies equation:

$$[\mathbf{P}]\times \overrightarrow{\boldsymbol{W}} = \lambda_{\max} \cdot \overrightarrow{\boldsymbol{W}} \qquad (4)$$

in other words 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 the (4) 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 p_{ij} 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 to measure the difference between these two set of values:

$$\text{CI} = \frac{\lambda_{\max} - m}{m-1} \qquad \text{CR=CI×RCI} \qquad (5)$$

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 (4) coincides with (1) 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 $\vec{W}$, the valuation matrix can be analyzed:

	W
criterion 1	w_1
…	
criterion *m*	w_m

for a comparison of alternatives, the different performances, assessed in function of the criteria considered, must be appropriately adimensional or, every element (indicator) of evaluation matrix should be transformed into a dimensionless measure which represents the utility $u\left(g\left(x\right)\right)$.

	criterion 1	…	criterion *m*		**W**
Alt 1	$u_1(g_1(1))$	…	$u_m(g_m(1))$	×	w_1
…		…			…
Alt *k*	$u_k(g_k(1))$	…	$u_m(g_m(k))$		w_k

⇩

V	$v(1)$	…	$v(k)$

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

$$v(k) = w_1 \times u_1\left(g_1\left(k\right)\right) + \cdots + w_m \times u_m\left(g_m\left(k\right)\right)$$

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

CONCLUSIONS

The proposed methodology wants to integrate different risk and economic factors. In a route optimization problem the objectives that serve as criteria for the calculation of routes may conflict with each other. The conflict among the objectives is present also among the units in which each objective function is measured. In order to be able to evaluate routes a Multiple-Attribute approach was proposed. Therefore, the model proposed concurs to determine an ordering of the different solutions giving a concrete tool to support decisions (DSS). Also, the model can be customized to other case studies and easily adapted to the methodology in developing countries.

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