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Assessement of areas exposed to damage by dangerous goods transportation

Application of Analytic Hierarchy Process method for land covers weighing

Fabio Borghetti, Paolo Gandini, Rosanna Iuliano, Giuseppe Pastorelli, Luca Studer
Mobility and Transport Laboratory
Design Department - Politecnico di Milano
Milano, Italy
info.trasporti@polimi.it

***Abstract* — The DESTINATION project, operating since 2010, proposed as its primary objective the implementation of a new information system called GIIS (Global Integrated Information System). The GIIS provides a platform for the sharing and analysis of data concerning dangerous goods transportation within the territories of the project: Canton Ticino, Piedmont Region, Lombardy Region, Autonomous Region of Aosta Valley and Autonomous Province of Bolzano Alto Adige. The GIIS is based on a risk analysis model related to the transport of dangerous goods, which is able to consider both human and environmental targets that are potentially exposed. The article describes the approach used to assess possible environmental targets in a consistent way with the goals of the project. By applying the AHP methodology, a weighting coefficient for non-human targets is defined, in order to homogenize the units of measurement of the potential damages of the exposed environmental targets, as well as to allow the algebraic sum of the risks.**

Keywords — Hazmat, Hazardous materials, Dangerous goods, Transport risk, Risk analysis, Safety, AHP.

I. Destination Project

The Destination Project (Dangerous Transport to New PreventTive Instruments), "Monitoring the transport of dangerous goods as a means of protection for the territory" started with the purpose of quantifying and managing the risk related to Dangerous Goods Transportation by road (DGT) and it is funded by the Italy/Switzerland Operational Program for Transfrontier Co-operation 2007-2013 Interreg. The Project involves as Partners: Piedmont Region, Lombardy Region, Region of Aosta Valley, Autonomous Province of Bolzano and the Canton Ticino (CH). Technical partners working on Destination are CSI Piemonte, 5T S.r.l. and the Mobility and Transport Laboratory - Politecnico di Milano.

The main objective was the development and implementation of the information system called GIIS (Global Integrated Information System), intended to monitor, collect and analyse data in order to prevent the risks caused by DGT. The GIIS, which is operational and not just experimental, offers public and private parties the opportunity to acquire, analyse, process and share data related to DGT, but also referring to anthropic and environmental vulnerabilities and to the resilience of the territory. By increasing the awareness of the danger rising from DGT and its consequent risk, the GIIS is even intended as a support tool for involved stakeholders, in order to have a more effective and efficient management of the different DGT phases (planning and prevention, on-trip assistance, emergency management in case of accident).

II. Risk Assessement

The implementation of the GIIS required the definition of a risk assessment model for DGT, in compliance with the classical formulation of the risk [1], which allows to consider the actual availability of data. The expression defined explains the factors considered indicative and reasonably measurable that contribute to risk. For these factors, the most appropriate unit of measurement and the functional dependency on the most significant variables of interest, characterized by subscripts, were defined:

- road link (*i*)
- substance (*j*), as considered by the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR)
- incident scenario with a specific threshold and a consequential damage area (*k*)
- type and susceptibility of targets (*m*)

The road link element used in the formula should be considered in particular as a conventional portion of road on which all the parameters for the risk characterization are uniquely defined (it could correspond to a one kilometre link, but its definition is independent from the actual length).

The general analytic formula for collectivity risk, or simply risk (societal risk for human exposure and environmental risk for non-human exposures), is reported in (1).

$$R_i = P_{is,i} \sum_j \left(P_{ADR,ij} \sum_k \left(P_{sc,ijk} \sum_m \left(F_{p,m} E_{ikm} S_{km} \left(1 - C_{ff,ikm} \right) \right) \right) \right) \quad (1)$$

Where:

R_i = cumulated risk for the collectivity (societal/environmental) referred to the *i*-th link [deaths/link/year] [damaged m^2_{eq} /link/year]

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$P_{is,i}$ = road hazard referred to the *i*-th link [vehicles involved in accident/link/year]

$P_{ADR,ij}$ = occurrence probability of a car accident involving a *j*-th ADR substance referred to the *i*-th link [ADR vehicles involved in accidents/vehicles involved in accidents]

$P_{sc,ijk}$ = occurrence probability of a *k*-th incident scenario with a specific threshold and a consequential damage area, involving the *j*-th substance, on the *i*-th link [incident scenario/ADR vehicles involved in accident]

$F_{p,m}$ = presence/weighing factor of the *m*-th potentially exposed target referred to specific temporal sets [equivalent involved inhabitants/equivalent exposed inhabitants][m^2_{eq}/m^2 exposed]

E_{ikm} = *m*-th target potentially exposed to a *k*-th incident scenario with a specific threshold and a consequential damage area (*k*), involving the j-th substance, on the *i*-th link [equivalent exposed inhabitants/incident scenario][exposed m^2/incident scenario]

S_{km} = susceptibility of the *m*-th target potentially involved in the *k*-th scenario [deaths/equivalent involved inhabitants][damaged m^2_{eq}/exposed m^2_{eq}]

$C_{ff,ikm}$.= resilience/copying capacity of the *m*-th target potentially exposed to a *k*-th incident scenario, involving the *j*-th substance, on the *i*-th link [-]

The overall features of the risk assessment model are described in detail in [2], [3], [4], [5]. The methodology for the assessment of F_p, i.e. the weighting factor related to environmental targets which is preparatory to the evaluation of risk environmental component, is described below.

III. Weighing Factor (F_P) for Non-Human Targets

The parameter F_p, a function only referring to the exposed target (subscript *m*), is intended, in case of non-human targets, to allow the "sum" of different potentially exposed targets (E parameter).

The non-human targets considered by Destination for the environmental risk assessment, consist of:

1. urbanized areas;
2. agricultural areas;
3. wooded areas;
4. cultural heritage;
5. surface waters.
6. protected areas and groundwater (considered as a kind of burden factor for the other targets, with respect to, de facto, overlapped layers).

These are heterogeneous targets and, although they can all be expressed in m^2 of surface exposed by approximation, they are not factually "summable" as they are when assessing damages caused by a DGT event because of their very different environmental values. Such heterogeneity goes in parallel with a real overlap of uses, physical features and functions on the territory that make insignificant an evaluation based on a mere sum of surfaces. The F_p coefficient was therefore introduced in order to homogenize the units of measurement of the potential damages of the exposed targets, as well as to allow the algebraic sum of the risks.

As part of the project, studies, research and technical-scientific literature references useful for this purpose were analysed. The aggregation of the surfaces of different land uses/covers is a debated matter, since the need has culturally risen to also extend the methods to assess impacts and costs/ benefits to environmental components. However, no suitable solution for the purposes of the project Destination was found. For example, the use of Storie-Villa index, proposed by several authors [6] [7], or its variations [8], allows to define an environmental dimensionless value for each land use considered, reported in an appropriate numerical scale, and thus to convert the surfaces in an equivalent area used as reference. However, it presents many complexities in the actual gathering of the data needed for an effective application, which makes this index suitable for an extremely detailed analysis (thus for small scale applications), but difficult to apply over large areas as the one considered by Destination. A second approach used in literature involves the use of a dimensional coefficient, transforming the real surfaces (expressed in m^2) into an economic value (€), thus allowing to sum the exposed surfaces (this time all expressed in €) . This solution was used widely, with different features, in many contexts [9] [10] [11] [12] [13] [14].

Despite the widespread application, this solution still requires the introduction of uncertainties and arbitrariness. The variety of soil functions, their variability in different geographical areas, the different administrative sensitivity to these functions, the costs related to depreciation and the intrinsic geographical monetary variability all make the existing approaches unsuitable to re-use, even for the purposes of Destination. Furthermore, all the possible solutions need one or more criteria (environmental, economic, social ...) in order to aggregate the different land uses considered. Consequently, for the purposes of Destination, a dedicated procedure was developed for the homogenization of the areas, which allows to take into account the different objectives (criteria) of the partners of the DGT risk assessment.

IV. Quantification of the F_P Parameter for Non-Human Targets within Destination

The implemented solution for land uses conversion within Destination is based on the mathematical theory AHP - Analytic Hierarchy Process [15], a decision-support method based on multicriteria analysis which involves the use of questionnaires to be submitted to stakeholders (i.e. project partners, in this case). The AHP technique is widely used for different scopes, even with applications in DGT [16], but with purpose significantly different from those investigated in this work.

The environmental targets defined within Destination completely cover the territory, but some types of target (groundwater and protected areas) are "overlapping" with others. Thus, the idea that underlies parameter F_p is to "quantify" the value of an area as a result of the possible simultaneous presence of a land use (urban, cultural, forest, agriculture, surface water) and of conditions of environmental quality (protected areas and groundwater), which actually act as a burden of risk and therefore of the numeric value of F_p. For this purpose, the following assumptions were made for the combinations of environmental targets:

- protected areas delimit an area of particular quality/ interest that can include any land cover;
- groundwater can only be combined with wooded and agricultural areas. Although they may also exist under any land cover, it is reasonable for the purposes of Destination to consider that (impervious) urbanized areas and cultural heritage and surface waters (favoured pathways for transport of pollutants) act as "protection" against damage of possible underlying waters.

A. *Methodological premises*

The quantification of the F_p parameter was then performed in two steps:

1. in the first step, the AHP methodology was rigorously applied to determine the relative value of each land cover;

2. in the second step, a structurally similar approach to AHP was adopted, though it was developed to estimate the burden factor due to the presence of protected areas and groundwater.

The product of the two partial factors (land cover and burden factor) allows the full definition of the combinations of an F_p matrix.

B. *Destination hierarchy for land cover*

The application of AHP requires first the definition of a hierarchical structure. This structure includes a first level of alternatives and a higher maximum level defined as supercriterion, which is the overall objective. There can then be criteria and sub-criteria at intermediate levels between the alternatives and the supercriterion. For this application a three-level structure was adopted:

Level 1: the alternatives are represented by different land covers.

Level 2: the intermediate criteria, identified by project partners through a process of discussion and sharing, are:

- Ecosystem value. It is the sum of the benefits provided by ecosystems with reference to the following categories:
  - life support (nutrient cycling, soil formation and primary production);
  - supply (production of resources such as drinking water, food, materials or fuel);
  - adjustment (climate and tides regulation, water purification, pollination and infestations control);
  - maintenance of wildlife biodiversity.
- Aesthetic-scenic-recreational value. It expresses:
  - the aptitude to host recreational activities of any kind;
  - the aptitude to become a place of leisure and to generate appreciation of the aesthetics and/or oriented to recreational use;
  - the contribution of soil's diversity to the structuring and qualification of landscape;
  - the attitude of an element of the territory to be perceived as a symbol of a broader local reality.
- Economic value. It includes the acquisition cost, the resources (monetary, temporal and social) needed to restore the condition preceding the event of alteration and the loss of incomes caused by the inability to fruition until full recovery.

Level 3: the supercriterion summarizes the three criteria identified and allows to determine the numerical values of F_p associated to individual alternatives, then to each single land cover considered.

C. *Application of the AHP method within Destination*

Within Destination, the AHP approach is aimed at quantifying the mutual "importance" of each land cover (alternatives) with reference to the objectives of the project. The land with the lowest score is taken as base measuring unit (equivalent surface m^2 or m^2_{eq}); the ratio between the scores of the other land covers and the one taken as reference (normalization) defines the equivalence factors, allowing the conversion of physical surfaces (expressed in m^2) into equivalent surfaces (expressed in m^2_{eq}).

For this purpose, in a three-level hierarchical structure like the one used, it is first necessary to obtain the final ranking of the alternatives with respect to each criterion defined, and then to sort the criteria with reference to the overall objective. More precisely, for each level, the pairwise comparison of the elements of that level with respect to one of the elements of the higher level produces ranking vectors.

Every single decision-maker, according to the AHP theory, answers questions from pairwise comparisons using a qualitative/quantitative scale, the Saaty scale, made of nine classes of preference (see Table I).

TABLE I. SAATY'S FUMDAMENTAL SCALE

Verbal scale	Numerical scale
Equal importance	1
Moderate importance	3
Strong importance	5
Very strong importance	7
Extreme importance	9

Pairwise comparisons performed for Destination were conducted through the preparation and distribution of a questionnaire, which is structured into fillable tables according to Saaty's rating scale. The questionnaire developed, which simulates an interview, is intended to provide the basic information that is considered necessary for these purposes. This approach has the advantage of simplifying data collection and increasing the size of the sample given the same amount of time spent. The questionnaire was distributed by Destination institutional partners of the project (Regions and Provinces) to their technicians and officials: each of them was called to answer for their competences, according to their training, experience and awareness gained.

The application of the AHP method within Destination included the following simplifications:

- The Destination team chose, in agreement with the institutional partners, not to develop a ranking vector for the intermediate criteria, thus considering them of equal importance. This choice means that the three criteria (ecosystem, aesthetic-scenic-recreational, economic) are considered equivalent, and that all of them equally contribute to define the environmental sensitivity of the Destination partnership. From the mathematical point of view, this convention means a ranking vector for the three criteria at the intermediate level, with reference to the general Destination objective, made of three equivalent values [0.33; 0.33; 0.33].
- All project partners are equally important

D. Destination ranking for land covers

The Destination team collected a total of 78 questionnaires: 47 from the Piedmont Region, 21 from the Lombardy Region, 6 from the Autonomous Region of Aosta Valley and 4 from Canton Ticino. Out of these, 70% satisfied the conditions of "coherence" according to the theory of the AHP method. The questionnaires with insufficient coherence were not processed. Having a sufficient amount of experts allowed not to repeat the interviews for all the cases of inconsistency. For each consistent decision-maker, the rankings of the land covers were first obtained with reference to each of the three criteria. Then the final ranking was made, always keeping elaborations separated for each decision-maker. Just after these steps, the results from all the decision-makers were aggregated. This occurred for each project partner. The last step was to calculate the combination of a single and overall ranking of land covers with reference to Destination's objective, i.e. the definition of equivalence factors. The choice to analyse, in a first phase, the results of questionnaires separately for each single partner allowed to appreciate similarities and differences of sensitivity on these issues, as well as a fruitful sharing of the results achieved. For all decision-makers, urbanized areas were recognized as the land cover with the least overall environmental value, but also with reference to each individual criteria considered. For this reason, the surface of urban areas was taken as the base measuring unit to which other land covers in m^2_{eq} are related. It was thus possible to obtain the ranking of different land covers within the project Destination, as shown in Fig. 1.

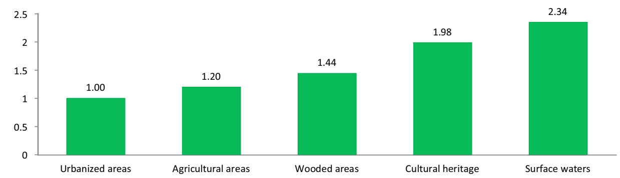

Fig. 1. Destination ranking for land covers

As it can be observed, surface waters are the target characterized by the highest environmental value, while for agricultural areas a value just above the urbanized areas is recognized.

More specifically, Fig. 2 and Fig. 3 reports the different approaches of Destination's partners. Lombardy and Piedmont, who contributed to the study with a larger number of interviewees, present a ranking vector that is very close to the overall Destination one. On the contrary, the results obtained are significantly different for the respondents from Aosta Valley and Canton Ticino.

	Lombardy	Piedmont	Canton Ticino	Aosta Valley	DESTINATION
Urbanized areas	1.0	1.0	1.0	1.0	1.0
Agricultural areas	1.3	1.2	0.8	1.0	1.2
Wooded areas	1.4	1.6	0.6	1.2	1.4
Cultural heritage	1.7	2.2	0.9	2.3	2.0
Surface waters	2.3	2.3	2.5	2.6	2.3

Fig. 2. Ranking for land covers, detailed by partners.

	Lombardy	Piedmont	Canton Ticino	Aosta Valley
Urbanized areas	0%	0%	0%	0%
Agricultural areas	11%	-2%	-29%	-17%
Wooded areas	-6%	10%	-56%	-14%
Cultural heritage	-14%	10%	-54%	15%
Surface waters	-3%	0%	5%	10%

Fig. 3. Deviation of land covers values from the overall Destination ranking. Values expressed in percentage.

It is also interesting to observe the different rankings obtained from the territories corresponding to the project partners, with reference to the three separate environmental criteria. Table II shows the differences among the ranking obtained by the same land cover, as a function of the criterion according to which they are valued and of the partner considered.

From the point of view of the ecosystem value, the most significant value, among different land covers, is recognized to surface waters, while the aesthetic-scenic-recreational and economic value are more typically experienced in the cultural heritage.

TABLE II. RANKING FOR LAND COVERS, DETAILED BY CRITERION AND PARTNER

Land cover	Lombardy	Piedmont	Canton Ticino	Aosta Valley	Destination
"Ecosystemic value" Criterion					
Urbanized Areas	1.0	1.0	1.0	1.0	1.0
Agricultural Areas	6.4	4.6	1.6	2.2	3.0
Wooded Areas	4.9	5.4	1.3	1.7	2.6
Cultural heritage	1.4	1.1	1.3	0.6	1.0
Surface waters	9.6	9.2	3.8	4.3	5.7
"Aesthetic-scenic-recreational value" Criterion					
Urbanized Areas	1.0	1.0	1.0	1.0	1.0
Agricultural Areas	0.8	0.8	0.8	0.9	0.8
Wooded Areas	1.7	2.1	1.2	2.7	1.8
Cultural heritage	2.6	3.8	1.6	5.3	3.1
Surface waters	2.0	2.2	3.9	3.8	2.9
"Economic value" Criterion					
Urbanized Areas	1.0	1.0	1.0	1.0	1.0
Agricultural Areas	0.6	0.6	0.6	0.4	0.6
Wooded Areas	0.5	0.5	0.1	0.5	0.4
Cultural heritage	1.3	1.7	0.5	2.0	1.3
Surface waters	1.0	0.9	1.3	1.2	1.1
"Destination" Supercriterion					
Urbanized Areas	1.0	1.0	1.0	1.0	1.0
Agricultural Areas	1.3	1.2	0.8	1.0	1.2
Wooded Areas	1.4	1.6	0.6	1.2	1.4
Cultural heritage	1.7	2.2	0.9	2.3	2.0
Surface waters	2.3	2.3	2.5	2.6	2.3

E. *Destination ranking for environmental value systems*

As specified, in order to estimate the contribution of environmental value systems to the value of land covers, the team used a procedure based on questionnaires and pairwise comparisons, which is structurally similar to the AHP. In this second case, interviewees are called to face binary comparisons between a land cover and the same land cover with an environmental value system. Technicians used, for consistency's sake, Saaty's fundamental scale, i.e. the same rating scale of the first phase for the definition of land covers ranking. Evaluation criteria were the same, too. Since it is not a classic AHP procedure (which gives as output a matrix of comparisons between more than two alternatives), the survey results were not processed by using the eigenvector method, but directly read and analysed. In particular, it was necessary to define, by sharing this topic with Destination partners, the maximum conventional burden factor that is determined by the single or simultaneous presence of the two systems of environmental value to which the survey results relate. The sensitivity of project technical partners suggested that all the systems of environmental value may correspond to a maximum burden multiplication factor that is equal to 2. It was thus possible to create a correlation between the judgments expressed in Saaty's fundamental scale [1,9] and the standardized scale adopted as convention [1,2], as shown in Table III. This equivalence was used to interpret the data provided by the questionnaires.

TABLE III. CORRELATION BETWEEN SAATY'S FUNDAMENTAL SCALE AND THE STANDARDIZED SCALE ADOPTED BY DESTINATION FOR ENVIRONMENTAL VALUE SYSTEMS.

Saaty's fundamental scale [1;9]		Standardized scale [1;2]
1	Equal	1.0
2		1.2
3	Moderate	1.3
4		1.4
5	Strong	1.6
6		1.7
7	Very strong	1.8
8		1.9
9	Extreme	2.0

The weight given by the totality of the technicians was found to be essentially homogeneous (~ 1.6), as well as almost equivalent for both environmental value systems and irrespective of the basis land cover considered. The greatest burden in terms of environmental loss is recognized to the simultaneous presence of surface waters and protected areas (see Table IV).

TABLE IV. VALUE OF ENVIRONMENTAL VALUE SYSTEMS

LAND COVERS	ENVIRONMENTAL VALUE SYSTEMS	
	Protected Areas	*Groundwater*
Urbanized Areas	1.6	
Agricultural Areas	1.5	1.6
Wooded Areas	1.6	1.6
Cultural heritage	1.5	
Surface waters	1.7	

A more detailed analysis of the results, by considering each partner separately, shows a very restrained deviation from the overall result of Destination (See Fig. 4, Fig. 5).

	Lombardy	Piedmont	Canton Ticino	Aosta Valley	DESTINATION
Urbanized areas in protected areas	1.5	1.5	1.9	1.5	1.5
Agricultural areas in protected areas	1.6	1.5	1.9	1.5	1.5
Wooded areas in protected areas	1.6	1.6	1.9	1.6	1.6
Cultural heritage in protected areas	1.5	1.5	1.9	1.5	1.5
Surface waters in protected areas	1.7	1.6	1.9	1.7	1.7
Agricultural areas and groundwater	1.6	1.6	1.9	1.6	1.6
Wooded areas and groundwater	1.6	1.6	1.9	1.6	1.6

Fig. 4. Ranking of environmental value systems by project partner

	Lombardy	Piedmont	Canton Ticino	Aosta Valley
Urbanized areas in protected areas	-2%	-1%	27%	1%
Agricultural areas in protected areas	0%	-2%	24%	0%
Wooded areas in protected areas	-1%	-1%	17%	-1%
Cultural heritage in protected areas	-3%	-1%	28%	-3%
Surface waters in protected areas	1%	-2%	15%	0%
Agricultural areas and groundwater	-2%	-1%	20%	-1%
Wooded areas and groundwater	-4%	0%	19%	-1%

Fig. 5. Deviation of the values given to environmental value systems at Destination average value. Values expressed in percentage.

Even the detailed analysis of environmental value systems, with reference to the three criteria considered and to the objective of Destination, shows no particular differences between partners or criteria, which indicates a substantial alignment of the partners' sensitivity to the burden factors considered.

V. RESULTS OF THE AHP APPLICATION FOR DESTINATION: F_p PARAMETER FOR NON-HUMAN TARGETS

The analyses carried out allowed to build the F_p matrix for non-human targets, which includes the coefficients of equivalence among land covers and the burden factors for environmental value systems. The structure of the matrix and the corresponding final values of the parameter F_p for non-human targets are the following (Table V).

TABLE V. F_p MATRIX FOR NON-HUMAN TARGETS.

LAND COVERS	ENVIRONMENTAL VALUE SYSTEMS		
	No system	***Protected Areas***	***Groundwater***
Urbanized Areas	1.0	1.5	
Agricultural Areas	1.2	1.9	1.9
Wooded Areas	1.4	2.4	2.3
Cultural heritage	2.0	3.0	
Surface waters	2.3	3.9	

The final results obtained allow the GIIS to assess, consistently with all the aims of the project Destination, any potential environmental damages resulting from a DGT event. GIIS applications for the purposes of land and transport planning (management of restrictions of transit to DGT vehicles, routing and re-routing actions, etc.) are therefore complete and comprehensive, also including environmental aspects that are considered significant and not negligible by the project partners.

In conclusion, the results achieved according to the approach described in this paper present the same limits and weaknesses of other methodologies found as potential references, especially as far as the introduction of subjectivities and uncertainties is concerned. However, these limitations are acceptable if compared to the benefits of having results that are specifically developed with a customized approach and not simply adapted from other studies.

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