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# Environmental vulnerability assessment in the vicinity of an industrial site in the frame of ARAMIS European project

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## Abstract

This work has been carried out in the framework of the ARAMIS project, which aims at developing a comprehensive procedure for assessing the risk level associated to an industrial site with respect to the surrounding environment. To this end, an index is defined which consists of the contribution of three terms, expressing the severity of the scenario consequences, the efficiency of the safety management and the vulnerability of the surrounding environment. The present work focuses on this last aspect concerning the determination of the vulnerability, of the area in the vicinity of an industrial site, of human, environmental (or natural) and material stakes. The applied methodology consists in identifying and quantifying the targets by the means of a geographical information system (GIS) and in assessing the contribution of each target on the basis of a multicriteria decision approach (Saaty method). The result is an operational tool allowing competent authorities, industrialists and risk experts to assess the vulnerability of the area surrounding an industrial site.

*Keywords:* ARAMIS; Environment vulnerability assessment; Geographical information system; Multi criteria decision method; Industrial site

## 1. Introduction

ARAMIS project aims at developing an integrated risk index based on, among others, the vulnerability of the environment surrounding an industrial site. Indeed, environmental vulnerability is usually scarcely taken into account in risk assessment, and its integration in ARAMIS project represents therefore an innovative aspect of great interest. The concept of vulnerability can be defined as "vulnerability is the degree of loss to a given element at risk, or set of such elements, resulting from the occurrence of a phenomenon of a given magnitude" [1]. Fig. 1 illustrates the problematic addressed when defining the environmental vulnerability, which may be summarized as follows: is area 1, which is composed of

human, environmental (or natural) and material targets, more or less vulnerable than area 2 also composed of human, environmental and material targets, but in different quantity and of different nature?

The idea here developed is to define a vulnerability index to identify and characterize the vulnerability of all possible targets located in the surroundings of a Seveso industrial site (vulnerability mapping). This requires first to establish the study area and define the targets of interest, then to identify and quantify the targets in the study area and, finally, to assess their vulnerability: this last step needs a specific methodology. In this work, a semi-quantitative approach to assess the vulnerability is adopted, which stands on a multicriteria decision method (Saaty's method) based on experts judgements. This method allows to take into account both the "status" of a specific target (qualitative approach) and the "enumeration" of that target (quantitative approach).

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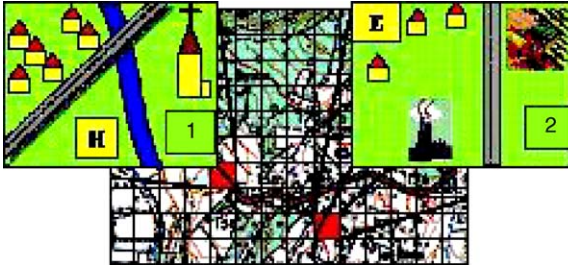


Fig. 1. The problematic of environmental vulnerability.

The paper is organised as follows:

- a summary of the developed methodology to assess the vulnerability;
- the implementation of the methodology on Geographical Information Systems (GIS);
- the application to vulnerability mapping of an industrial site;
- some perspectives and conclusions.

## 2. Characterisation of a study area

In this part, the objective is to propose some features of a typical study area in terms of dimension and mesh size whatever the territory assessed.

### 2.1. Size of the study area

On the base of previous studies [1,2] and data concerning the effects distances of major accidents, a study area of 400 km<sup>2</sup> has been chosen (a square of 20 km × 20 km). This dimension area is expected to include all the consequences of flammable and explosive events and the greatest part of the consequences of toxic events, but it will not include the impact area of a very large toxic cloud under particular atmospheric conditions. However, the grid size of 20 km × 20 km will fit our scope, requiring a reasonably limited amount of territorial information. In order to have a more accurate representation of the vulnerability index, it is convenient to cut the study area into meshes. The size of these meshes is of 250 m in a first approach but it may, in the future, depend on the source—targets distance. In fact, close to the industrial site it may be interesting to have a smaller size of the meshes (for example, 50 m × 50 m) and far from the industrial site to have a bigger size of the meshes (for example 500 m × 500 m).

### 2.2. Targets typologies

It is necessary to propose a set of target types to characterise with accuracy the environment, while keeping in mind the importance of the transferability of the method and its flexibility. Indeed, a proper balance must be found between the number of targets to be taken into account and the limitations due to the multicriteria decision method.

First of all, targets were divided into three categories and each of these categories is then detailed in a list of generic targets:

- Human (*H*)
  - Staff of the site (*H*<sub>1</sub>)
  - Local population (*H*<sub>2</sub>)
  - Population in an establishment receiving public (*H*<sub>3</sub>)
  - Users of communication ways (*H*<sub>4</sub>)
- Environmental (*E*)
  - Agricultural areas (*E*<sub>1</sub>)
  - Natural areas (*E*<sub>2</sub>)
  - Specific natural area (*E*<sub>3</sub>)
  - Wetlands and water bodies (*E*<sub>4</sub>)
- Material (*M*)
  - Industrial site (*M*<sub>1</sub>)
  - Public utilities and infrastructures (*M*<sub>2</sub>)
  - Private structures (*M*<sub>3</sub>)
  - Public structures (*M*<sub>4</sub>)

### 2.3. Available databases

A GIS (Geographical Information System) based approach allows to easily manage the problem of characterizing the study area and its targets. Most information can be obtained from two databases, Corine Land Cover [3] and TeleAtlas [4].

The Corine Land Cover [3] database provides homogeneous geographical information about land use in each country of Europe. The main information included in this database is topographical maps, vegetation and type of forest maps and finally soil and network description.

There are five main types of territory description:

- artificial territory
- land for agricultural use
- forest and natural areas
- humid areas
- water areas

The five previous types are described by 44 classes in order to characterise the natural environment.

The TeleAtlas database [4] consists in local data collection activities in all European countries and in the USA.

The included themes are:

- road and street centre-lines
- address areas
- administrative areas
- postal districts
- land use and cover
- railways
- ferry connections
- points of interest: built-up areas
- settlement centres
- water

These two databases fill most of the needs concerning natural environment and man made targets. As far as human targets are concerned, specific data provided by each country must be used. The information concerning the population can be obtained through national census organizations, for example the INSEE for France [5] and Istat in Italy [6]. Data are usually available for district or census unit.

To use these population data, some rules must be assumed to allocate a number of people to each mesh included in a district, as discussed in the paragraph concerning the quantification of environmental targets. If more precise results are required, information at the cadastral level should be taken into account. This second approach is more time consuming than the first one.

It has to be pointed out that other more specific information concerning some important environmental features, such as parks or protected natural zones of faunistic and floristic interest are available from national environmental organisations, such as APAT in Italy, or ZNIEFF in France.

Finally, some other information, such as those concerning the industrial site, has to be provided directly from the user, since it is not available to the general public.

### 3. The vulnerability index

#### 3.1. Generalities on the multicriteria decision method of Saaty [7]

In a general way, decision-taking is a complex process which is not only based on a set of information about a subject, but depends also on the representations of the members of the decision group regarding their vision of the reality. Furthermore, personal preferences and persuasion can have more importance in the process of decision than a clear and rigorous logic.

A multicriteria hierarchical method brings an organisation of information and appreciation, which intervenes in the process of decision-taking.

The purpose of the method of Saaty is an assessment of priorities. To this end, the first point is to have a consensus on the objective, then in a second time, to decompose the complex and not structured situation in its main components. The types of results can be a classification, an allocation of numerical values of subjective judgments or the aggregation of judgements to determine criteria having the highest priorities. The multicriteria hierarchical method allows to obtain a decision-taking by a group in a consensual way due to a better coherence of judgement.

The multicriteria hierarchical method of Saaty (Saaty, 1984) is based on three main steps:

- a description of the studied system (some elements and criteria are proposed in order to characterise the situation);
- a construction of hierarchies (to organize the elements and the criteria to answer to the problematic);

Table 1  
Scale of binary comparison

Degree of importance	Definition
1	Equal importance of two elements
3	Weak importance of an element in comparison to the other one
5	Strong importance of an element in comparison to the other one
7	Certified importance of an element in comparison to the other one
9	Absolute importance of an element in comparison to the other one
2, 4, 6, 8	Intermediate values between two appreciation
1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9	Reciprocal values of the previous appreciation

- an assessment of priorities (based on expert judgements);
- a validation of coherence.

The construction of a hierarchical structure requires the creation or the identification of links between the various levels of this structure.

Each element or criteria of a hierarchical structure takes place at a given level of the structure. Its upper level corresponds to the global objective (or dominant element). Some binary comparisons are done between all the elements of a given level according to the element of the upper level, in order to rank the elements among them. The various levels of a hierarchy are, consequently, interconnected.

A complex situation can be analysed by a systematic approach with the help of the hierarchical structure. The priorities have to be assessed. This process is done by a comparison of elements two by two (binary comparison). It gives the ranking of elements according to their relative importance. Finally, the logical coherence confirms the whole applied process. To do the binary comparisons, it is necessary to use a scale based on classic numerical variables or more qualitative variables contributing to take into account qualitative aspects as showed in the Table 1.

#### 3.2. Application to the determination of the vulnerability index

On the based of the Saaty methodology, the first part consists in the description of the environment (Fig. 2) in order to have a good understanding of the situation. To this aim, three typologies are proposed:

- a typology of targets which is composed of three main classes of targets (human, environmental and material).



Fig. 2. Description of the system.

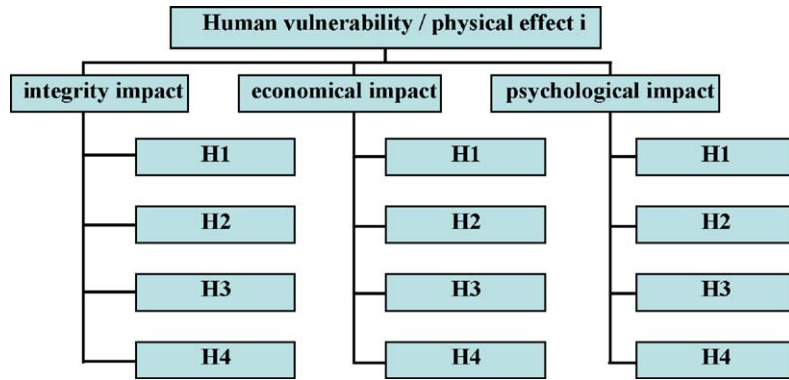


Fig. 3. Hierarchical structure for the human vulnerability per physical effect characterisation.

Each main class of targets is characterised by four types of targets as described in the Section 2.3.

- a typology of physical effects. Four types of effects are considered:
  - overpressure;
  - thermal flux;
  - gas toxicity;
  - liquid pollution.
- a typology of impacts. Three impacts due to physical effects are considered to characterise the effects of major accidents on targets:
  - sanitary or integrity impact which qualifies the effect on respectively human or environmental and material structures;
  - economical impact which qualifies an effect in terms of loss of production or of cost of rehabilitation;
  - psychological impact which qualifies an effect in terms of influence on a group of people.

It is then necessary to organise these typologies in order to answer to the vulnerability problematic.

Therefore, the following step consists in the structuring of the information. It is ensued from the following definition of the vulnerability.

For a class of targets and a given physical effect, the vulnerability of each type of targets in comparison with the other one is evaluated by means of binary

according to the characterisation criteria, which are the three impacts.

The result is the vulnerability of one class of target for one physical effect. The associated hierarchical structure is presented in Fig. 3 for the human vulnerability.

For a class of targets, the importance of each physical effect in comparison with another one is evaluated by the way of binary comparisons: the result is the vulnerability of one class of target (Fig. 4). Finally, the vulnerability of each class of targets is compared to the others, leading to the global vulnerability (Fig. 4).

The same hierarchical structure applies to environmental and material vulnerability.

From this definition and from hierarchical structures, the matrixes and the functions of the vulnerability index are deduced. The matrixes are translated into a questionnaire, which allows to collect the expert judgement for the evaluation of each coefficient of the vulnerability functions.

### 3.3. The vulnerability factors and functions

Thirty-eight experts have been consulted in an individual way. The repartition of experts per Country and type are presented in Figs. 5 and 6: a great part of them were French or Italian.

Concerning the type of experts, about 60% were risks experts (from public or private structures).

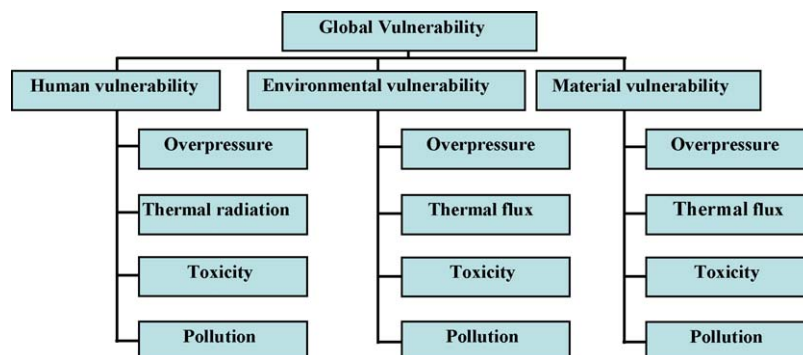


Fig. 4. Hierarchical structure of the global vulnerability characterisation.

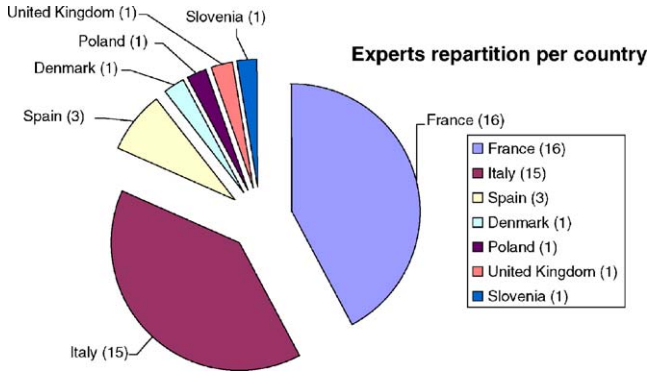


Fig. 5. Experts repartition per country.

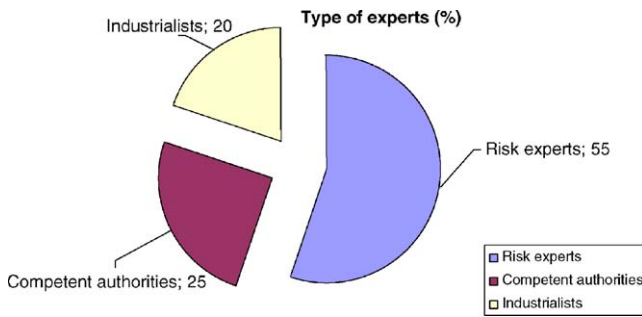


Fig. 6. Experts repartition per type.

A specific treatment was required to aggregate the appreciation of the above mentioned experts. Each appreciation was aggregated by the use of geometrical mean. So, one questionnaire, which is an aggregation of the appreciations of all consulted experts, is obtained. All evaluations are reported into the matrixes and the factors of vulnerability can be assessed. Results are given in the following paragraph.

To assess the vulnerability factors of each function, the eigenvectors of the matrixes must be calculated. The solutions correspond to the factors of vulnerability. Tables 2–5 present the results. To validate the coherence of expert judgement appreciation a ratio of coherence (RC) must be calculated. If it is lower than 10% [7] for each matrix, all results could be considered as coherent.

The results obtained for the global vulnerability function (Table 2) show the great importance (about 75%) of human vulnerability. The vulnerability factor of environmental targets represents 20%, while the material vulnerability represents only 5% of the function.

Table 2  
Global vulnerability function

Function	RC%
$V_{\text{global}} = 0.752 \times V_H + 0.197 \times V_E + 0.051 \times V_M$	0.17

For human targets (Table 3), the main effect is “gas toxicity” (47%). The effects of “overpressure” and “thermal radiation” have about the same importance (respectively 24% and 23%). On the contrary, the effect of “liquid pollution” has a weak influence on human targets (only 7%).

For human targets and for all the physical effects, the sanitary impact is the dominating impact (about 65%). The psychological impact represents about 25% of the vulnerability factors and the economical impact represents only 10%. For the physical effects of “overpressure” and “thermal radiation”, the type of targets  $E_3$  (specific natural area) has the higher vulnerability factor for all impacts. Concerning liquid pollution, the type of targets  $E_4$  (wetlands and water bodies) has an important vulnerability. The two other categories  $E_1$  and  $E_2$  (agricultural area and natural area) seem to be less vulnerable to this physical effect than  $E_3$  and  $E_4$ . Concerning material targets (Table 5), the effects of overpressure and thermal radiation represent the main parts of the vulnerability factors (respectively 45% and 41%). For an overpressure effect and a thermal radiation effect, the integrity and the economical impacts are more important than a psychological impact. On the contrary, for a gas toxicity effect and a liquid pollution effect, the economical and the psychological impacts are more important than the integrity impact. By considering the effects of gas toxicity and liquid pollution, the factors of vulnerability have about the same value for all types of targets except for the type of target  $M_1$ . Concerning a thermal radiation effect, the factor of vulnerability for an economical impact of the type of target  $M_1$  has a dominating value.

All the ratios of coherence (RC) are lower than 10%, so the vulnerability factors based on the thirty-eight questionnaires mentioned above are validated.

However, this information can be completed. Therefore, Eq. (1) can also be rewritten as Eq. (5) so that the global vulnerability can be then obtained as:

$$V_{\text{global}} = V_{\text{op}} + V_{\text{tr}} + V_{\text{tox}} + V_{\text{poll}} \quad (5)$$

With op, overpressure; tr, thermal radiation; tox, toxicity; poll, pollution

This allows to generate other functions of vulnerability (Eqs. (6)–(9), to map vulnerability layers specific of a particular physical effect ( $V_{\text{op}}$ ,  $V_{\text{tr}}$ ,  $V_{\text{tox}}$ ,  $V_{\text{poll}}$ ).

$$V_{\text{op}} = 0.182 \times V_H^{\text{op}} + 0.014 \times V_E^{\text{op}} + 0.023 \times V_M^{\text{op}} \quad (6)$$

$$V_{\text{tr}} = 0.169 \times V_H^{\text{tr}} + 0.029 \times V_E^{\text{tr}} + 0.021 \times V_M^{\text{tr}} \quad (7)$$

$$V_{\text{tox}} = 0.350 \times V_H^{\text{tox}} + 0.055 \times V_E^{\text{tox}} + 0.004 \times V_M^{\text{tox}} \quad (8)$$

Table 3  
Human vulnerability functions

Functions	RC%
$V_H = 0.242 \times V_H^{op} + 0.225 \times V_H^{tr} + 0.466 \times V_H^{tox} + 0.067 \times V_H^{poll}$ (2)	0.43
<b>Overpressure</b>	
$V_H^{op} = 0.666 \times (V_H^{op})_S + 0.111 \times (V_H^{op})_E + 0.222 \times (V_H^{op})_P$	0
$(V_H^{op})_S = 0.366 \times H_1 + 0.278 \times H_2 + 0.233 \times H_3 + 0.24 \times H_4$	2.5
$(V_H^{op})_E = 0.404 \times H_1 + 0.340 \times H_2 + 0.139 \times H_3 + 0.117 \times H_4$	1.72
$(V_H^{op})_P = 0.150 \times H_1 + 0.368 \times H_2 + 0.282 \times H_3 + 0.200 \times H_4$	4.57
<b>Gas toxicity</b>	
$V_H^{tox} = 0.735 \times (V_H^{tox})_S + 0.069 \times (V_H^{tox})_E + 0.196 \times (V_H^{tox})_P$	0.35
$(V_H^{tox})_S = 0.227 \times H_1 + 0.424 \times H_2 + 0.227 \times H_3 + 0.122 \times H_4$	0.57
$(V_H^{tox})_E = 0.351 \times H_1 + 0.351 \times H_2 + 0.189 \times H_3 + 0.109 \times H_4$	0.57
$(V_H^{tox})_P = 0.140 \times H_1 + 0.456 \times H_2 + 0.263 \times H_3 + 0.141 \times H_4$	0.55
<b>Thermal radiation</b>	
$V_H^{tr} = 0.648 \times (V_H^{tr})_S + 0.122 \times (V_H^{tr})_E + 0.230 \times (V_H^{tr})_P$	0.3
$(V_H^{tr})_S = 0.354 \times H_1 + 0.354 \times H_2 + 0.161 \times H_3 + 0.131 \times H_4$	1
$(V_H^{tr})_E = 0.409 \times H_1 + 0.350 \times H_2 + 0.158 \times H_3 + 0.082 \times H_4$	0.86
$(V_H^{tr})_P = 0.167 \times H_1 + 0.333 \times H_2 + 0.333 \times H_3 + 0.167 \times H_4$	0
<b>Liquid pollution</b>	
$V_H^{poll} = 0.594 \times (V_H^{poll})_S + 0.157 \times (V_H^{poll})_E + 0.249 \times (V_H^{poll})_P$	4.62
$(V_H^{poll})_S = 0.212 \times H_1 + 0.497 \times H_2 + 0.191 \times H_3 + 0.100 \times H_4$	0.86
$(V_H^{poll})_E = 0.283 \times H_1 + 0.490 \times H_2 + 0.152 \times H_3 + 0.076 \times H_4$	0.57
$(V_H^{poll})_P = 0.138 \times H_1 + 0.479 \times H_2 + 0.256 \times H_3 + 0.128 \times H_4$	0.53

Table 4  
Environmental vulnerability functions

Functions	RC%
$V_E = 0.071 \times V_E^{op} + 0.148 \times V_E^{tr} + 0.277 \times V_E^{tox} + 0.503 \times V_E^{poll}$ (3)	0.4
<b>Overpressure</b>	
$V_E^{op} = 0.333 \times (V_E^{op})_S + 0.333 \times (V_E^{op})_E + 0.333 \times (V_E^{op})_P$	0
$(V_E^{op})_S = 0.122 \times E_1 + 0.227 \times E_2 + 0.424 \times E_3 + 0.227 \times E_4$	0.53
$(V_E^{op})_E = 0.289 \times E_1 + 0.246 \times E_2 + 0.289 \times E_3 + 0.175 \times E_4$	3.36
$(V_E^{op})_P = 0.168 \times E_1 + 0.239 \times E_2 + 0.395 \times E_3 + 0.198 \times E_4$	3.36
<b>Gas toxicity</b>	
$V_E^{tox} = 0.691 \times (V_E^{tox})_S + 0.160 \times (V_E^{tox})_E + 0.149 \times (V_E^{tox})_P$	0.48
$(V_E^{tox})_S = 0.286 \times E_1 + 0.142 \times E_2 + 0.286 \times E_3 + 0.286 \times E_4$	0
$(V_E^{tox})_E = 0.340 \times E_1 + 0.140 \times E_2 + 0.239 \times E_3 + 0.280 \times E_4$	3.36
$(V_E^{tox})_P = 0.205 \times E_1 + 0.169 \times E_2 + 0.338 \times E_3 + 0.288 \times E_4$	3.36
<b>Thermal radiation</b>	
$V_E^{tr} = 0.550 \times (V_E^{tr})_S + 0.240 \times (V_E^{tr})_E + 0.210 \times (V_E^{tr})_P$	1.58
$(V_E^{tr})_S = 0.195 \times E_1 + 0.231 \times E_2 + 0.426 \times E_3 + 0.148 \times E_4$	2.54
$(V_E^{tr})_E = 0.227 \times E_1 + 0.227 \times E_2 + 0.424 \times E_3 + 0.122 \times E_4$	0.57
$(V_E^{tr})_P = 0.200 \times E_1 + 0.200 \times E_2 + 0.400 \times E_3 + 0.200 \times E_4$	0
<b>Liquid pollution</b>	
$V_E^{poll} = 0.710 \times (V_E^{poll})_S + 0.155 \times (V_E^{poll})_E + 0.135 \times (V_E^{poll})_P$	1.58
$(V_E^{poll})_S = 0.227 \times E_1 + 0.122 \times E_2 + 0.227 \times E_3 + 0.424 \times E_4$	0.53
$(V_E^{poll})_E = 0.278 \times E_1 + 0.123 \times E_2 + 0.231 \times E_3 + 0.367 \times E_4$	2.55
$(V_E^{poll})_P = 0.140 \times E_1 + 0.140 \times E_2 + 0.262 \times E_3 + 0.458 \times E_4$	0.53

Table 5  
Material vulnerability functions

Functions	RC%
$V_M = 0.446 \times V_M^{\text{op}} + 0.410 \times V_M^{\text{tr}} + 0.069 \times V_M^{\text{tox}} + 0.075 \times V_M^{\text{poll}}$ (4)	0.39
<b>Overpressure</b>	
$V_M^{\text{op}} = 0.571 \times (V_M^{\text{op}})_I + 0.286 \times (V_M^{\text{op}})_E + 0.143 \times (V_M^{\text{op}})_P$	0
$(V_M^{\text{op}})_I = 0.200 \times M_1 + 0.400 \times M_2 + 0.200 \times M_3 + 0.200 \times M_4$	0
$(V_M^{\text{op}})_E = 0.288 \times M_1 + 0.338 \times M_2 + 0.169 \times M_3 + 0.205 \times M_4$	3.36
$(V_M^{\text{op}})_P = 0.143 \times M_1 + 0.286 \times M_2 + 0.286 \times M_3 + 0.286 \times M_4$	0
<b>Gas toxicity</b>	
$V_M^{\text{tox}} = 0.200 \times (V_M^{\text{tox}})_I + 0.400 \times (V_M^{\text{tox}})_E + 0.400 \times (V_M^{\text{tox}})_P$	0
$(V_M^{\text{tox}})_I = 0.142 \times M_1 + 0.286 \times M_2 + 0.286 \times M_3 + 0.286 \times M_4$	0
$(V_M^{\text{tox}})_E = 0.204 \times M_1 + 0.347 \times M_2 + 0.204 \times M_3 + 0.246 \times M_4$	3.36
$(V_M^{\text{tox}})_P = 0.100 \times M_1 + 0.300 \times M_2 + 0.300 \times M_3 + 0.300 \times M_4$	0
<b>Thermal radiation</b>	
$V_M^{\text{tr}} = 0.443 \times (V_M^{\text{tr}})_I + 0.387 \times (V_M^{\text{tr}})_E + 0.169 \times (V_M^{\text{tr}})_P$	1.58
$(V_M^{\text{tr}})_I = 0.246 \times M_1 + 0.298 \times M_2 + 0.210 \times M_3 + 0.246 \times M_4$	3.36
$(V_M^{\text{tr}})_E = 0.400 \times M_1 + 0.200 \times M_2 + 0.200 \times M_3 + 0.200 \times M_4$	0
$(V_M^{\text{tr}})_P = 0.143 \times M_1 + 0.286 \times M_2 + 0.286 \times M_3 + 0.286 \times M_4$	0
<b>Liquid pollution</b>	
$V_M^{\text{poll}} = 0.260 \times (V_M^{\text{poll}})_I + 0.413 \times (V_M^{\text{poll}})_E + 0.327 \times (V_M^{\text{poll}})_P$	4.62
$(V_M^{\text{poll}})_I = 0.127 \times M_1 + 0.313 \times M_2 + 0.280 \times M_3 + 0.280 \times M_4$	1.
$(V_M^{\text{poll}})_E = 0.204 \times M_1 + 0.347 \times M_2 + 0.204 \times M_3 + 0.246 \times M_4$	3.6
$(V_M^{\text{poll}})_P = 0.127 \times M_1 + 0.280 \times M_2 + 0.313 \times M_3 + 0.280 \times M_4$	1.2

$$V_{\text{poll}} = 0.050 \times V_H^{\text{poll}} + 0.099 \times V_E^{\text{poll}} + 0.004 \times V_M^{\text{poll}} \quad (9)$$

When one of the contributions related to a physical effect is missing, due to the absence of relevant accidental scenarios in the industrial site under study, the contributions of this physical effect must be neglected also in Eqs. (2)–(4), which give the vulnerability of each class of targets: accordingly Eqs. (1) and (5) will give the same value of global vulnerability.

To complete the functions of vulnerability, quantification factors of each type of targets are implemented. They are defined in the following paragraph.

### 3.4. Quantification factors

The quantification factors are those accounting for the “quantity” of environmental targets in the study area. A quantification factor is defined as a dimensionless variable, assuming values in the range 0–1, where 0 indicates the absence of the target in the area and 1 indicates that the quantity of that target in the area reaches its expected maximum.

Therefore, the quantification factors aims at obtaining a normalized counting of each detailed type of targets ( $H_1$ – $H_4$ ,  $E_1$ – $E_4$  and  $M_1$ – $M_4$ ).

#### 3.4.1. Human targets

The quantification factor  $H_i$  relevant to each of the  $i$ -th types of human targets in the area are determined as:

$$H_i = \frac{N_i}{N_{\text{max}}} \quad (10)$$

with  $N_i$  total number of people of the  $i$ -th human target type and  $N_{\text{max}}$  maximum number of people of the  $i$ -th human target type, in the area under exam.

Accordingly, in order to determine the quantification factors for human targets, it is preliminarily necessary to set the maximum value, which the number of people belonging to each  $i$ -th human category type can reach in the area,  $N_{\text{max}}$ .

#### 3.4.2. Environmental targets

All environmental targets can be derived from commercial databases, and GIS tools allow to determine the areas they cover within the study zone.

Accordingly, the quantification factor  $E_i$ , relevant to the  $i$ -th types of environmental targets in the area can be determined as:

$$E_i = \frac{A_i}{A} \quad (11)$$

with  $A_i$  extension of the area covered by the  $i$ -th type of environmental target within the boundaries of the area under exam ( $\text{km}^2$ ) and  $A$  extension of the area under exam ( $\text{km}^2$ ).

### 3.4.3. Material targets

Most material targets can be derived from commercial databases, which, however, may not account for some specific targets, such as the industrial site, or for some outstanding targets, such as vital infrastructures (for material target type 2) or monuments (for material target type 4).

The quantification factor  $M_i$ , relevant to the  $i$ -th types of material targets in the area is:

$$M_i = \frac{A_i}{A} \quad (12)$$

with  $A_i$  extension of the area covered by material target within the boundaries of the area under exam ( $\text{km}^2$ ). However, Should some outstanding target (of type 2 and 4 alone) be present, the quantification factor is modified as follows:

$$M_j = \frac{A_j}{A} + \sum_k \frac{I_{j,k}}{I_{\max_j}} \quad (13)$$

with  $j$  equal to 2 or 4,  $I_{j,k}$  a factor representing the importance of the  $k$ -th outstanding targets of the  $j$ -th type of specific targets present in the area under exam and  $I_{\max}$  maximum value of the importance of the  $j$ -th outstanding target. In fact, being very difficult to assign a “value” to outstanding targets, it can be obtained based on a relative scale of importance.

## 4. Operational GIS tool for vulnerability mapping

The approach described in section has been conveniently implemented in a GIS tool. In order to assess the vulnerability in the zone of interest, the following steps have to be performed (see Fig. 7):

- select the study area and divide it into meshes;
- assess the vulnerability for each mesh, by identifying and quantifying the detailed target types of the categories (human, environment and material) included into the mesh;
- calculate the vulnerability indexes of the meshes;
- map the results.

These actions should be repeated for all the meshes of the studied area.

The study area will be a square centred on the industrial site. Most required information concerning location and type of the various targets are rather easily available from commercial databases, as described in Section 2.

The GIS tool can be developed with any commercial GIS software, for example MapInfo [8] and ArcView [9]: the examples shown in the paper were obtained with MapInfo. In any case, the tool provides the user with procedures for selecting the study area, dividing it into meshes, and identifying and quantifying the different types of targets into each mesh. The quantification step is fully automated for the tar-

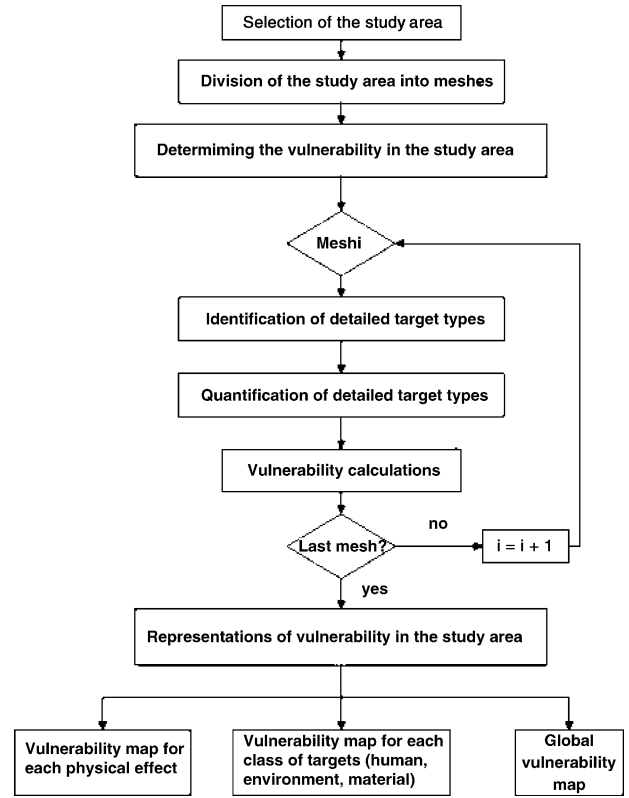


Fig. 7. Structure of the GIS tool for vulnerability mapping.

gets belonging to natural and built-up environment, based on the ratio of the area covered by each target of this type to the area under exam. The same procedure cannot be adopted for human targets, where the quantification factors have to be determined based on the maximum number of persons expected in the area. Default values are suggested to obtain the quantification factors [10].

The vulnerability values obtained in the previous phases can be mapped based on a scale of vulnerability, which translates the values of vulnerability indexes into classes of vulnerability.

Three types of results can be obtained:

- a cartographic representation of the global vulnerability in the study area;
- a cartographic representation of the vulnerability of a class of target (human, environmental or material);
- a cartographic representation of the vulnerability of a physical effect for a class of targets.

## 5. Application to the vulnerability mapping of an industrial site

In order to validate the methodology it was applied on several test cases. One specific case is developed in this article in order to show the type of vulnerability results that can be obtained.

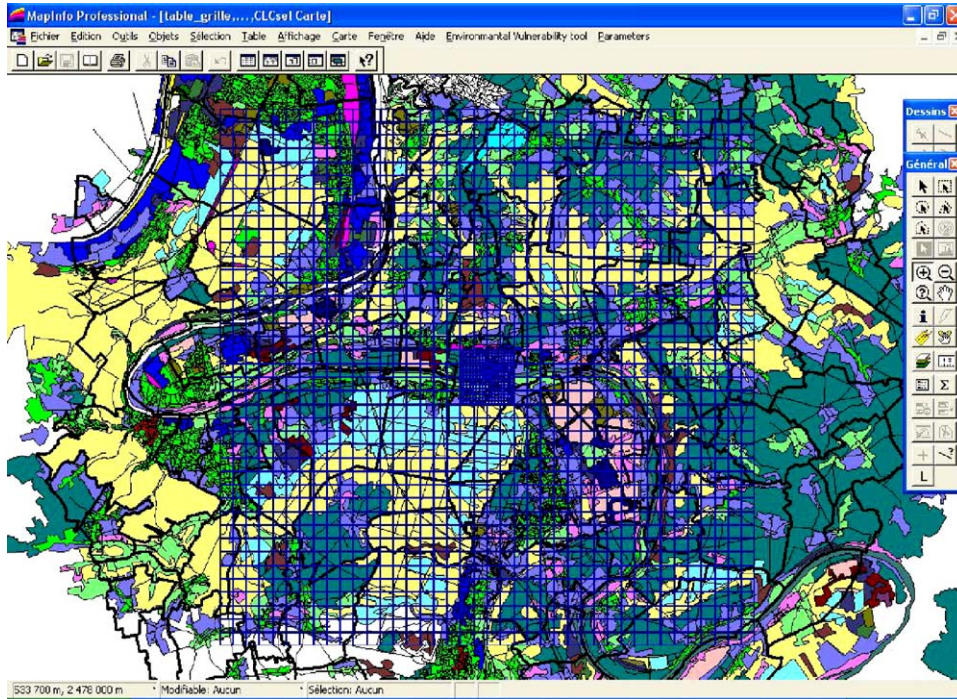


Fig. 8. Study area of the M-ral site.

## 5.1. Test case

The test site is the M-Real installation located near the town of Rouen in Seine Maritime region (France).

### 5.1.1. Description of the environment of the M-REAL site

The study area (Fig. 8) is composed of two grids:

- the main grid is a square of 20 km per 20 km with meshes of 500 m per 500 m;
- the inner grid is a square of 2 km per 2 km with meshes of 50 m per 50 m.

The inner grid allows to obtain a more precise representation of the vulnerability close to the industrial site.

This environment contains various targets which are detailed in Figs. 9 and 10.

Human stakes (Fig. 9), are mainly composed of districts with a very low and low density (ranging from 0 to 1000 people per square kilometre). Only about 20% of the study area presents districts with a medium value of density (between 1000 and 2000 people per kilometre square).

Natural and material stakes are mainly composed of agricultural areas, forests and semi natural areas (Fig. 10). The remaining part of the study area is characterised by artificial areas, wetlands and water bodies.

From this first description, one can say that the vulnerability for the whole area might be low or medium. Nevertheless, by using the vulnerability methodology, the maps obtained give an acute result of the value of vulnerability and also

the location of sensitive spots of vulnerability of the study area.

### 5.1.2. Presentation and analysis of vulnerability results

In this part, two different sets of vulnerability maps are presented and commented, which are:

- a set of vulnerability maps for each type of targets (human, environmental and material) and a map of global vulnerability;
- a set of vulnerability maps for each physical effect (overpressure, thermal radiation, toxicity and pollution).

The human vulnerability (Fig. 11) is very low over the whole study area. Indeed, the human vulnerability is strongly correlated to the population density and to urban or semi urban areas (artificial areas). Only the artificial areas present some spots of vulnerability with a low value of vulnerability due to the low population density in our study area.

The inner grid is characterized with a very low vulnerability except for the industrial site where there are about 600 workers.

A large part of the study area is characterized with a medium vulnerability value (Fig. 12).

Only the part, which corresponds to the artificial area, has a low value of vulnerability. In the inner grid, the presence of water bodies increases the value of environmental vulnerability.

The material vulnerability map (Fig. 13) underlines some specific spots of medium vulnerability mostly due to the

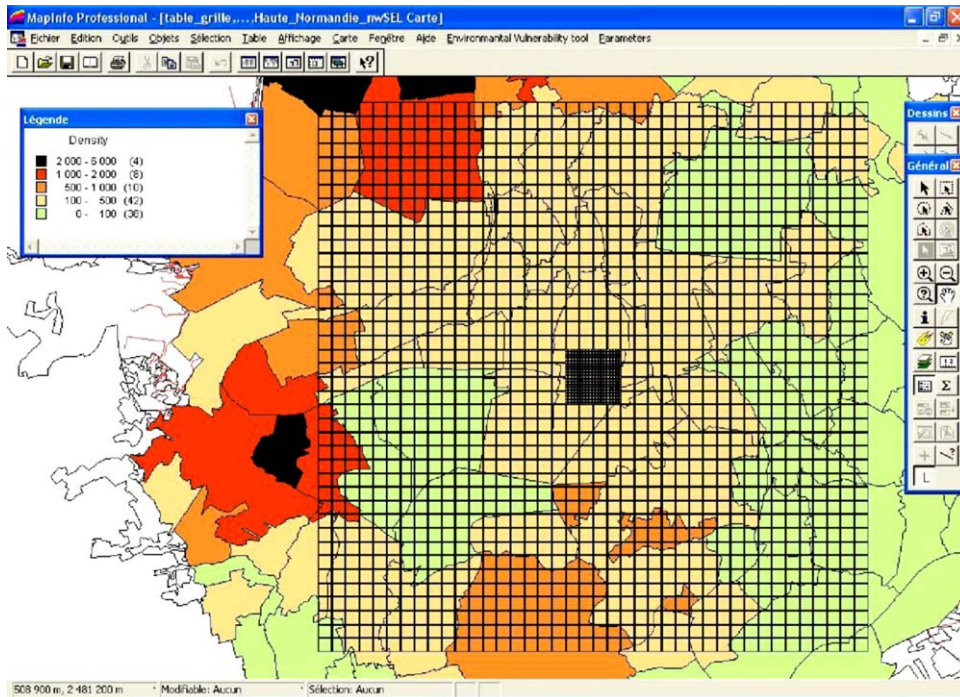


Fig. 9. Human stake of the study area.

location of artificial areas in the study area. In the inner grid, close to the industrial site, two spots of vulnerability are present.

From the comparison of the three maps (human, environmental and material) we can deduce that the spatial location of the most vulnerable zones is really similar for the human and

the material targets, as expected. We can also point out that the spatial location of most vulnerable areas on the environmental vulnerability map are opposite from those for human or material vulnerability maps.

From the three previous maps, the global vulnerability map (Fig. 14) can be deduced.

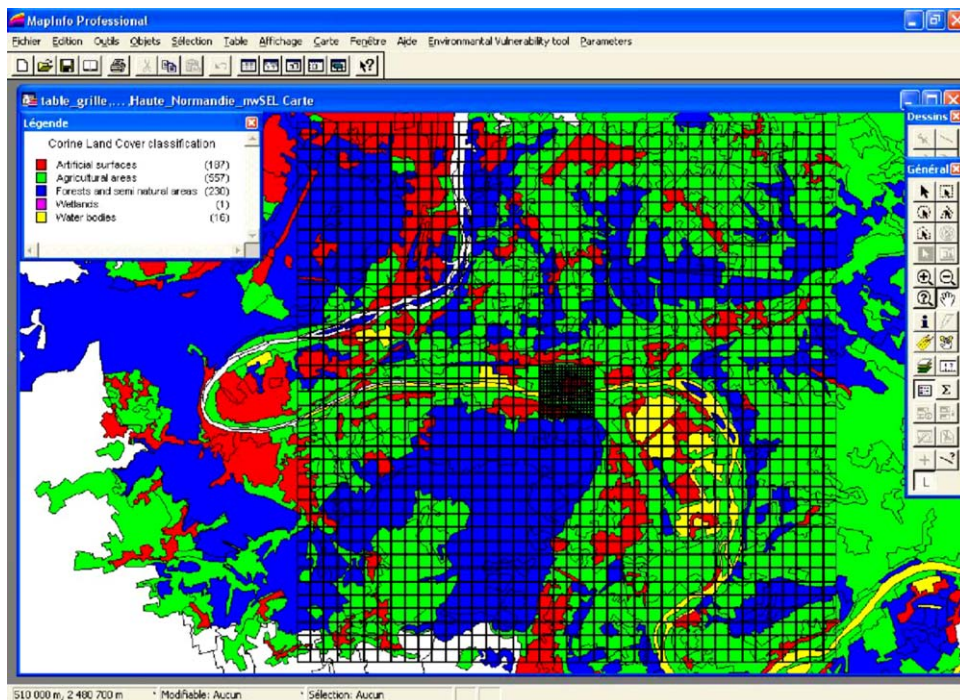


Fig. 10. Natural and material stakes of the study area.

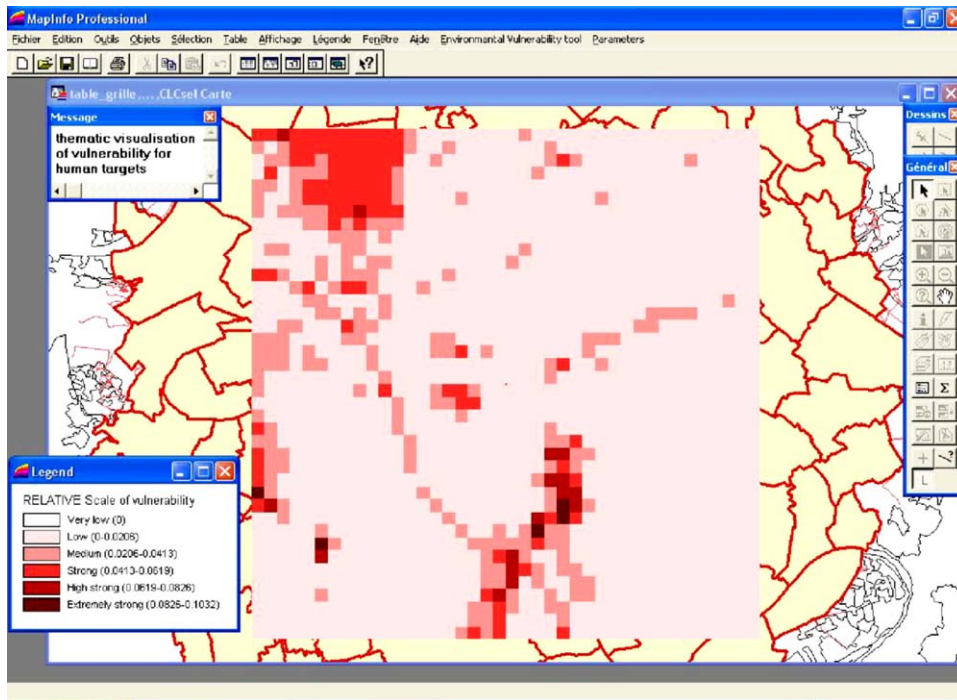


Fig. 11. Map of the human vulnerability.

The global vulnerability is weak for this study area. The map is clearly linked, even for the spots of higher vulnerability to the map of human vulnerability, which represents 75% of global vulnerability.

The vulnerability is low for overpressure and thermal radiation, and medium for toxicity and pollution effects. Concerning the vulnerability for overpressure maps, thermal radiation and toxicity, the location of the most vulnerable

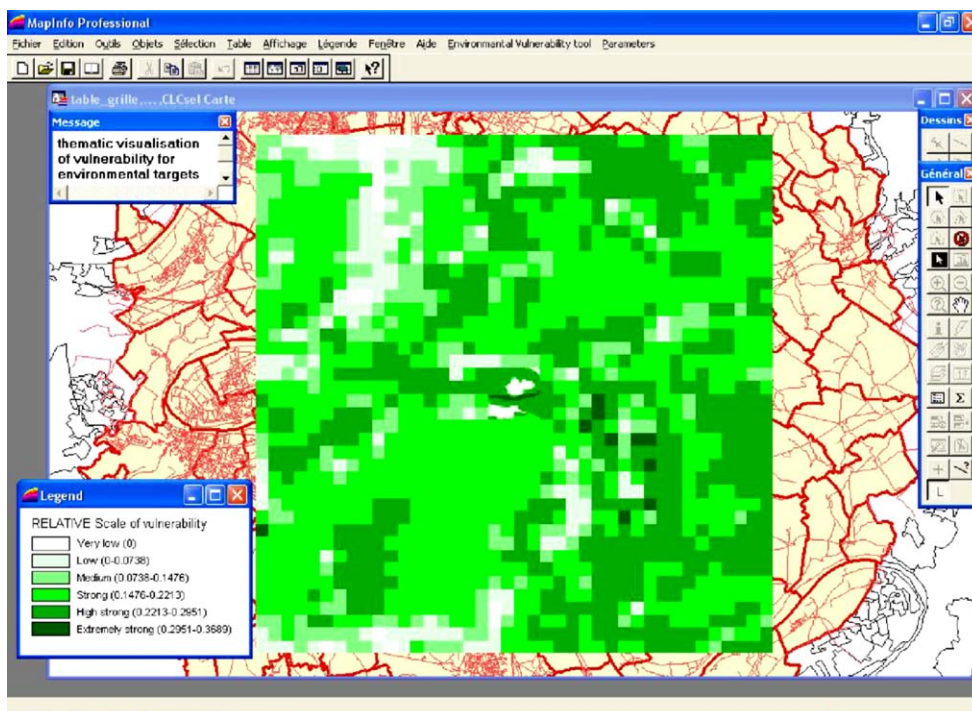


Fig. 12. Map of environmental vulnerability.

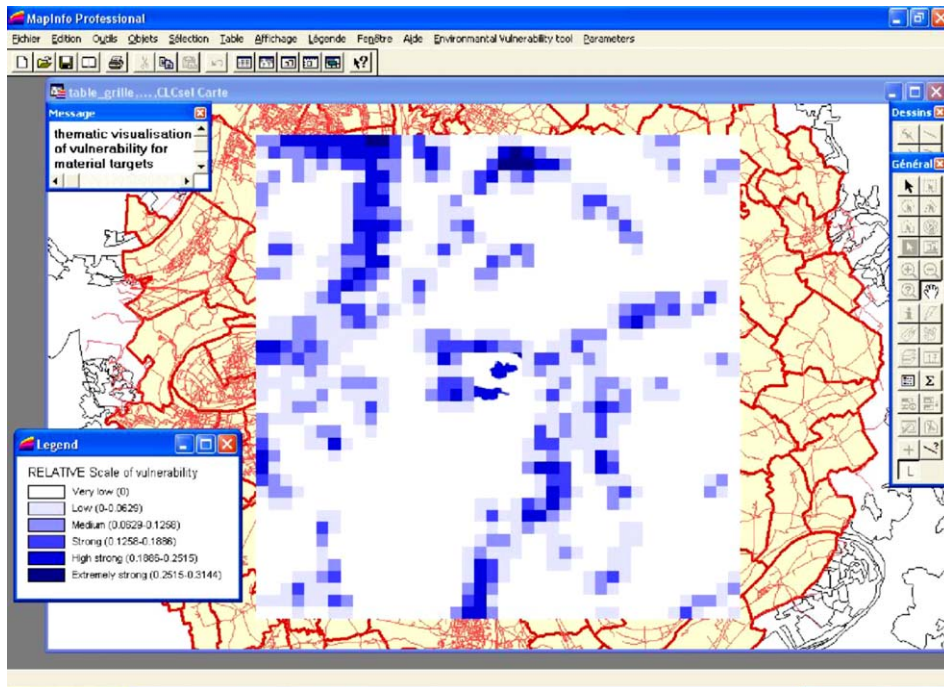


Fig. 13. Map of material vulnerability.

areas are linked to human vulnerability. For pollution effect, the spots of vulnerability are linked to natural environment (Fig. 15).

The vulnerability layers relevant to each physical effect ( $V_{op}$ ,  $V_{tr}$ ,  $V_{tox}$  and  $V_{poll}$ ) related to the industrial site under exam should then be compared with the corresponding severity maps. These two representations (severity and

vulnerability) provide the end users, which may be the industrialists, the risk analysts and/or the competent authorities, with a complete picture of the situation in the area surrounding the industrial site. This information not only allows to draw considerations on the risk of a specific industrial site in order to validate the level of confidence in safety, but may also highlight some dangerous situations, from a vulnerability

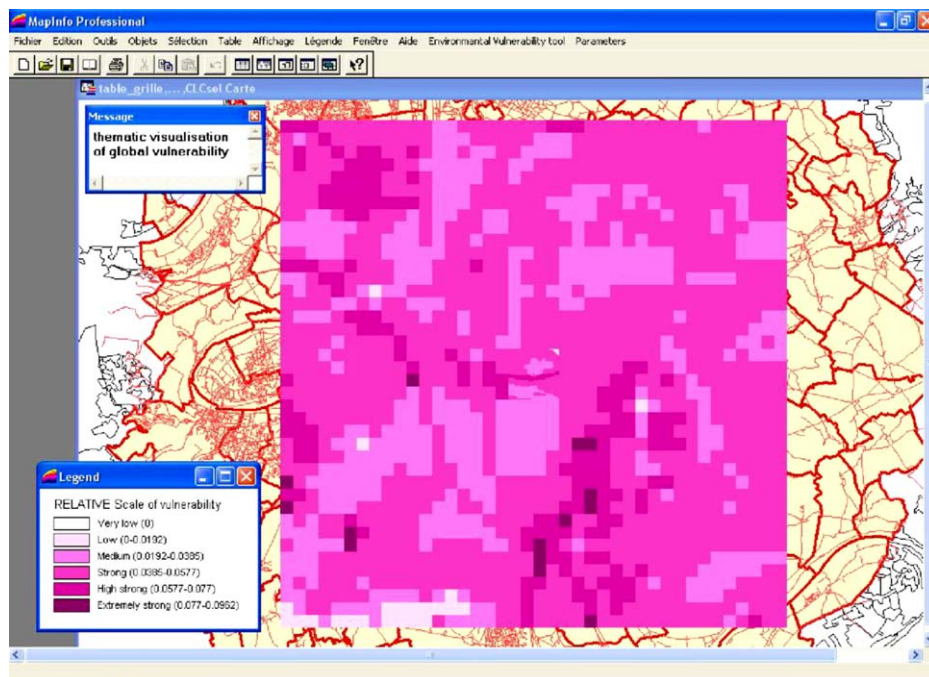
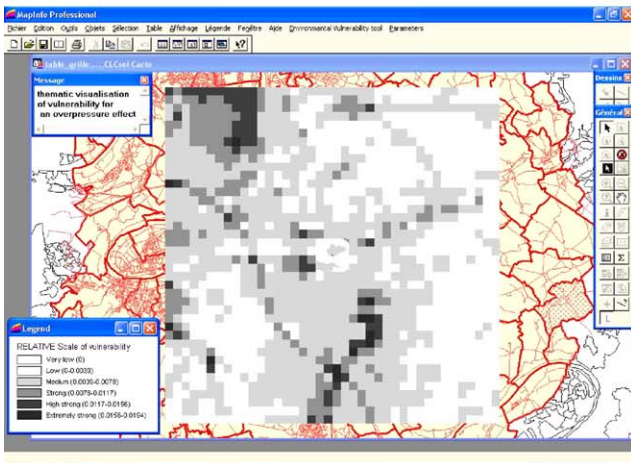
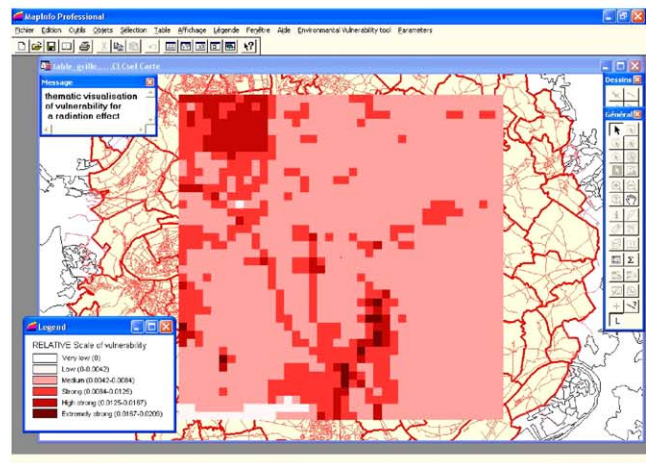


Fig. 14. Map of global vulnerability.

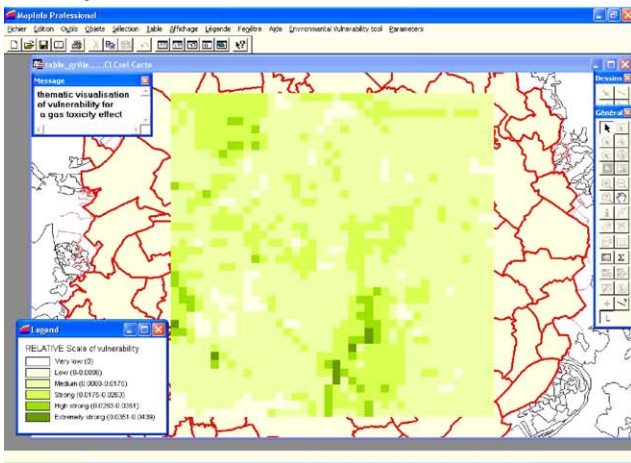
### Overpressure



### Thermal radiation



### Toxicity



### Pollution

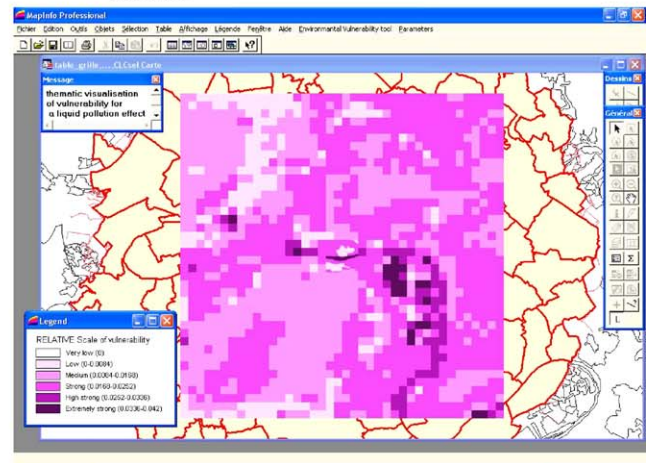


Fig. 15. Maps of vulnerability for each physical effect.

or a severity point of view, which require to be managed in order to improve the level of safety of the industrial site.

## 6. Perspectives and conclusions

A structured methodology is proposed to map the vulnerability in the area surrounding an industrial site. This methodology is based on the use of expert judgement and hierarchical structures to answer the problem of vulnerability calculation and on the quantification of the different types of environmental targets within the area. The methodology has been implemented within a GIS using the most common standards (ArcView, MapInfo) to make available an operational tool for risk managers, like competent authorities, industrialists and the risks experts to evaluate the vulnerability maps (global, for each target, and for each physical effect). The needed information about the targets, with the only exception of the industrial site data, can be extracted from commercial databases, and the user is assisted in all the steps from the selection of the study area and the grids, to the identification and quantification of the targets, while the

vulnerability calculations are completely automated. Using the tool, the end users will have a formalised representation of the situation of the environment to be compared to severity representation in order to effectively manage the risk.

The approach outlined in this work was applied to some real industrial sites, selected for testing the ARAMIS methodology, determining the vulnerability of the surrounding area. The results of these tests allowed to assess the capability of the proposed approach to actually represent a valid operational tool providing a detailed picture of the situation of the environment in order to suitably manage industrial risks.

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