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Elise Beck, Christiane Weber, Michel Granet. Application of the fuzzy logic to the study of the exposure to dangerous industries. The case of the urban area of Mulhouse (Haut-Rhin, France).. 14th European Colloquium on Theoretical and Quantitative Geography, Sep 2005, Tomar, Portugal. 13p. halshs-00201870

HAL Id: halshs-00201870

<https://shs.hal.science/halshs-00201870>

Submitted on 6 Oct 2023

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APPLICATION OF THE FUZZY LOGIC TO THE STUDY OF THE EXPOSURE TO DANGEROUS INDUSTRIES

The case of the urban area of Mulhouse (Haut-Rhin, France)

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The present study is part of a larger research which aims at addressing the conjunction of the seismic and industrial risks. It is applied to the urban area of Mulhouse, a medium sized French city. In this paper, the focus is done on the evaluation of the exposure to a dangerous industry. We chose to evaluate it by using the fuzzy sets theory (to a lesser extent the fuzzy logic). This method is still not widely spread in the field of the industrial risks, although it seems to provide many advantages. The different steps of an application of the fuzzy logic to the evaluation of the exposure to dangerous industries will be presented, as well as some concrete results for the urban area of Mulhouse. The whole study is carried out within a geographic information system (GIS).

KEYWORDS

Industrial risk, exposure to dangerous industries, GIS, fuzzy sets theory, urban area, Mulhouse.

INTRODUCTION

Cities and urban areas are dangerous sites, as they accumulate high densities of population as well as many human industrial activities. Some of them can represent a threat for the population. This has been clearly illustrated by the Toulouse's (France) recent accident, in September 2001, when the explosion of chemical products caused the death of 30 persons. Despite the Seveso European and national legislations, many people live close to dangerous industries like oil tanks, chemical or nuclear plants. That is why it is important to consider these populations and hence to acquire a better knowledge on industrial risks to enhance risk mitigation. The evaluation of the exposure to an industrial danger can be done using different methods. The fuzzy sets theory, which has been used in various domains since the 1950's, shows interesting advantages to this problematic. In this paper, after having presented the case study and the general purpose, we shall describe the general principles of the fuzzy sets theory and of the fuzzy logic, as well as their advantages to the study of risks. We shall end by presenting preliminary results for the urban area of Mulhouse (France).

GENERAL CONTEXT

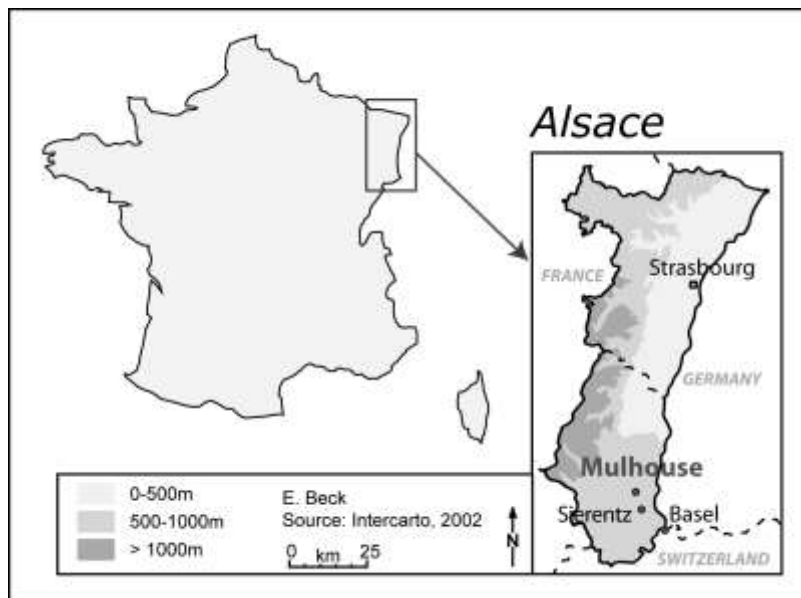
Case Study

The present study is part of a larger research which takes place in the urban area of Mulhouse, a city located in the north-eastern part of France, close to the Swiss and German borders (map 1). This city can be considered as a "multirisk" area, as it is exposed to several natural and technological risks: floods, mud flows, earthquakes, dangerous industries (chemical plants...), networks of hazardous materials transport and a dam. Among all these different threats, the research focuses on the seismic and the industrial risks.

Mulhouse is located in the Upper Rhine Graben, where the general stress field (oriented North-West/South-East) is due to the collision of the European and African Plates, which leads to the reactivation of inherited faulting systems. The seismicity is low to moderate, however, some catastrophic events like the Basel's earthquake (1356, with macroseismic intensity $I_0=IX-X$), could occur. This earthquake is considered as the strongest seismic event in Western Europe for the last thousand years, and its consequences were

dramatic in the context of the fourteenth century.

Several dangerous industrial sites are located in the urban area of Mulhouse (map 2): two chemical plants (one being specialized in the transport of chemical materials), an important site with oil tanks and a freight station. The latter is considered as a dangerous one because of the large amount of hazardous materials which are stored there or travel through the station. According to the French legislation, all these sites are characterized by a PPI (for "Plan Particulier d'Intervention"). This emergency plan defines a zoning for each dangerous industry. This zoning corresponds to the area concerned by the consequences of an accident, according to the worst scenario determined by the "studies of dangers". Map 2 shows the location of the four dangerous sites and their corresponding PPI zoning. We can notice that one of the two PPI zonings of the freight station totally includes the city of Mulhouse. Moreover, two places show a higher level of danger as the corresponding PPI zonings are superimposed (around the freight station and around the TYM industry). The present French legislation does not take into account neither this concentration of industrial risks nor the conjunction of two risks (seismic and industrial). An important issue is to know the consequences of such multiplication of risks to prevent some major disaster.



Map 1: Location of the urban area of Mulhouse.

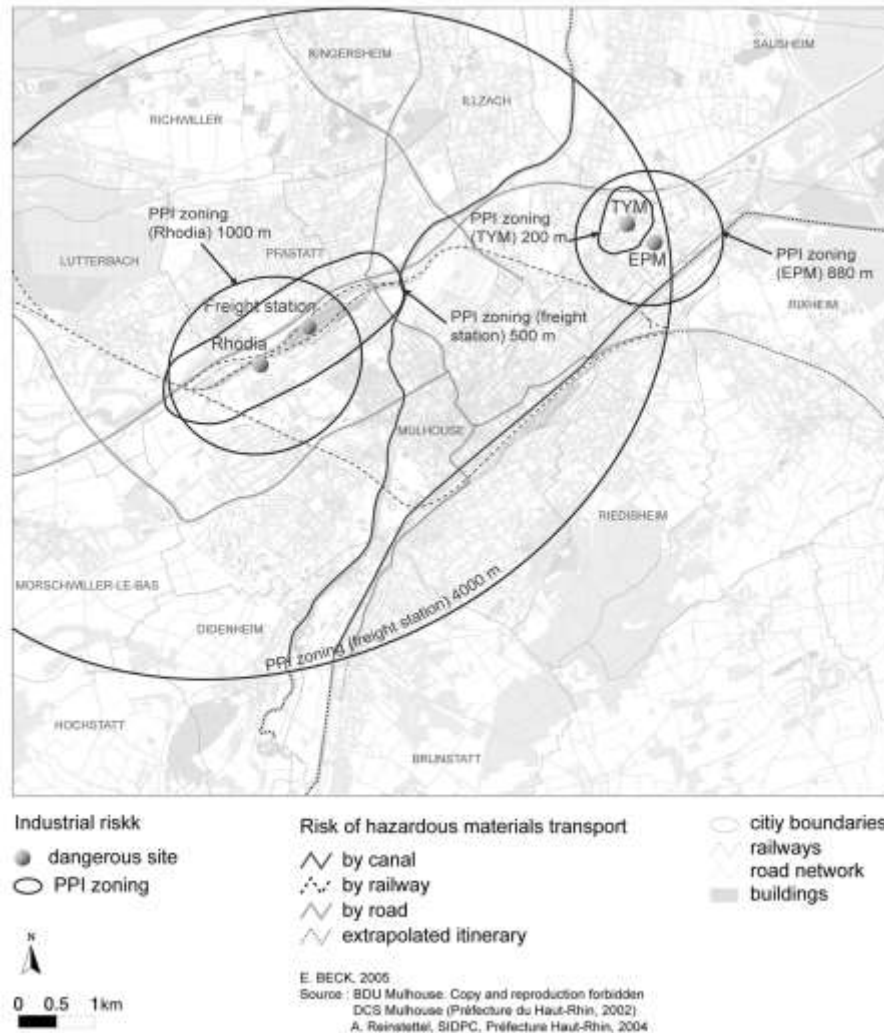
Finally, Mulhouse concentrates 200 000 inhabitants (1999 census), which illustrates the vulnerability of the region. Moreover, many industrial activities take place in this area, as for example an important car factory which employs about 12 000 persons. The vulnerability of the urban area city is also due to the organization of the road and railways networks (map 2), which totally hem the city. This results in urbanization problems and could also lead to serious difficulties in the management of a major crisis like a strong earthquake. We can easily imagine that the emergency services would hardly succeed in moving in the city.

General purpose

We have seen that the urban area of Mulhouse is exposed to several different risks that somewhere accumulate. The general research aims at assessing the conjunction between them. In other words, its objective is to evaluate the impact of a strong earthquake on the urban system of Mulhouse, and particularly on the dangerous industries [2], using a geographic information system (GIS). What could happen if an earthquake similar to the Basel's one occurred in a near future? In order to answer this question, we first of all need to evaluate the seismic and industrial risks. As a matter of fact, a good mitigation of risks starts with a good knowledge of the phenomena. Then, if we consider that the risk is the

result of the combination between hazard and vulnerability, it is necessary to characterize the vulnerable elements and to estimate the industrial and seismic hazards. In the case of dangerous industries, we would rather use the term “accident” than “hazard”.

The study is carried out within a geographic information system (GIS). This tool has proved to be very efficient in the field of risks [11]. For example, it allows to arrange, analyse and represent spatial data. In that way, it provides the possibility of modelling phenomena like risks by combining layers of hazard and vulnerability.



Map 2: Location of the dangerous industries in the urban area of Mulhouse.

Different methods can be used to evaluate the exposure to dangerous industries. The final choice of the method depends on the scale of study (national, regional, local) and on the data that are available or that can be acquired in a reasonable time. Rather than evaluating the consequences of an explosion, a fire or a pollution, which requires many data that are frequently inaccessible, we decided to represent the exposure of the population and the buildings to these threats. This exposure is to some extent symbolized by the PPI zoning, which is obtained from several studies of dangers. However, the largest zoning defined for this emergency plan corresponds to a zoning of constant diameter around the dangerous site, and this representation is not satisfying. Without neglecting the information provided by the PPI zoning, we

preferred to moderate its delimitations and particularly the rigidity of its limits: how should we interpret the fact that a building is located on the edge of the zoning? And what about two houses located on both sides of this limit: does that mean that the house located out of the PPI is not exposed to the industrial danger? It seemed necessary to integrate this uncertainty in our study. The fuzzy sets theory allows to take into account this uncertainty, this is why it is applied to the evaluation of the accumulated exposure to dangerous industries. The area of exposure to dangerous industries can thus be compared to a "fuzzy geographical space", as defined by Rolland-May [17], since its limits are fuzzy. Thus, the fuzzy sets theory can be applied to our study.

The originality of this approach does not come from the fact that we apply the fuzzy sets theory to environmental or geographic problems, since many other authors used this method [8, 13, 17, 18]. However, it rather lies in the choice of this approach for the evaluation of the exposure to dangerous industries, much more often considered using probabilistic models [10, 19].

METHODOLOGY

General Principles of the Fuzzy Sets Theory and the Fuzzy Logic – Advantages to the Study of Risks

The fuzzy sets theory is an extension of the sets theory defined by Cantor [7]. According to him, an element belongs or does not belong to a given set. The intermediate situation does not exist, which can become constraining when, for example, the spatial limits of the given unit are not well defined or not precise. In opposition, the theory of the fuzzy sets, stated by Zadeh in the 1960's [20], makes it possible to define degrees of membership to a fuzzy set, with degrees varying between 0 and 1 (fig. 1). The sets theory defined by Cantor can be considered to some extent as a particular case of the fuzzy sets theory, where all the membership degrees are either 0 or 1.

The fuzzy sets theory is a general theoretical frame for the use of mathematical, statistical or logical fuzzy operations. In our case, we chose the fuzzy logic and the fuzzy mathematics.

The application of the fuzzy sets theory and the fuzzy logic to a given field can be declined in four steps [21].

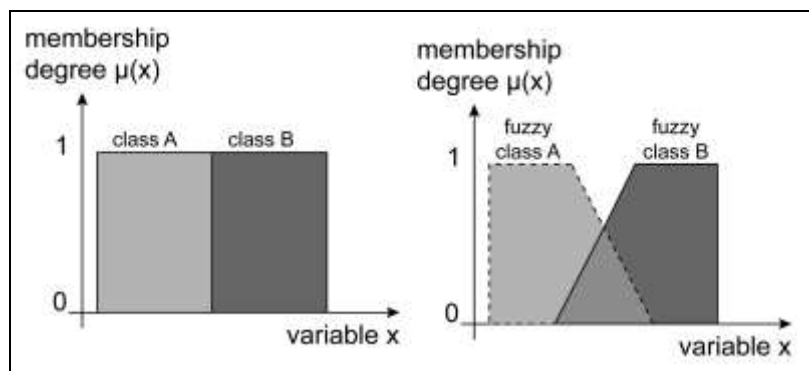


Figure 1: Membership function of a given variable x: the sets theory (according to Cantor) (left) vs the fuzzy sets theory (according to Zadeh) (right).

First of all, the input and output variables (i.e. the variables which will be integrated in the analysis) must be chosen. In our case, each variable corresponds to a data layer which will be integrated in the GIS. Then, a membership function is applied to each input variable. The membership function allows to associate with each element of a given set a real number in the interval [1;0]. This real number corresponds to the membership degree of the element to the set. The membership function can take very various shapes (linear, triangular, bell-shaped, etc.). This first step requires to consider the literature, experiments and the experience and knowledge of experts. The step of the fuzzification is illustrated by figure 2 with the example of a variable called "distance to a dangerous industry". We can notice on figure 2 the use of linguistic variables ("low, mean, high").

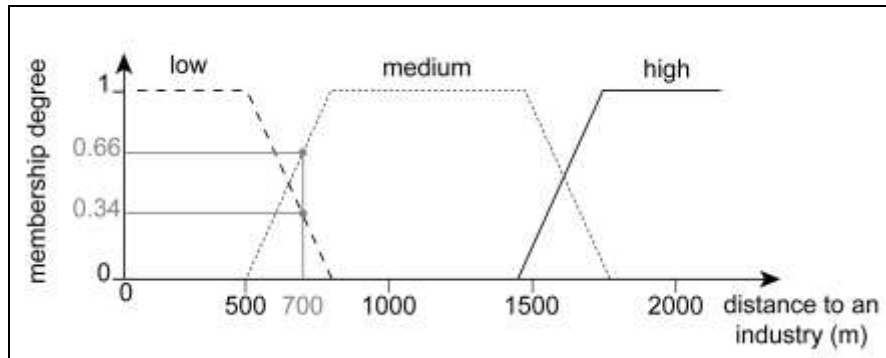


Figure 2: Example of membership function of the variable “distance to a dangerous industry”. The distance “700 m” belongs to the fuzzy set “low distance” with a membership degree of 0.34 and to the fuzzy set “medium distance” with a degree of 0.66 (from Griot [12]).

Once all the variables are “fuzzyfied”, the aggregation operators (or fuzzy operators) have to be chosen. They stand for logical combinations (or numerical combinations, depending on which approach we choose) between the input variables and correspond to numerical or Boolean operations between the membership degrees. The output variable is actually the result of the combination between the input variables. Many different fuzzy aggregators are available, but the five most used are: the “fuzzy AND”, the “fuzzy OR” (fuzzy logic), the fuzzy sum, the fuzzy product and the gamma operator (fuzzy mathematics) [1]. For example, if we applied the “fuzzy OR” to our problematic, we would obtain the following rule: *if* the distance to an industry where a fire could occur is small, *OR if* the distance to an industry where an explosion could occur is small, *then* the total exposure to a dangerous industry is high. The choice of the operators depends on the problematic and the objective that has to be reached. For example, the “fuzzy OR” leads to results that are controlled by the maximum value of the different membership degrees. As advised by Bonham-Carter [4], it is preferable to combine different operators in a model.

The third step is simply the application of the aggregation operators, i.e. the simulations. Several simulations are usually necessary in order to calibrate the model.

The final step consists in coming back to the context, in other words, in proceeding to a “defuzzification”, which corresponds to the transformation of the membership degrees (issued from the combination of the input variables) to output variables.

Of course, among the different methods used to evaluate hazards in general, we could retain another one than the fuzzy sets theory. Each method has advantages and drawbacks: the fuzzy sets theory and the fuzzy logic also have.

The fuzzy logic is a flexible method, since it is used in various domains [6], including in the field of risks (susceptibility to landslides [8]; consequences of an earthquake on buildings [9]). Concerning the variables, the fuzzy sets theory has the advantage to be used either for qualitative or quantitative variables, and to analyse them on comparable ranges of values. Moreover, as indicated by its name, it allows to integrate variables with high uncertainties (in particular uncertainties of location). In addition, it allows to use multi-source, multi-scale and heterogeneous data [3].

The second advantage lies in its capacity to represent a smooth transition from a state to another [5], which is a major asset in the study of risks. For example, if one considers a PPI zoning, its definition is geometrical, since, at the present time, it corresponds to a circle (or an ellipse) of a certain diameter. When a building is crossed by the limit of the zoning, it is, by definition, inside the PPI, but also apart from this one. What is really its statute? One can thus rather think of smooth transitions between the state of being in a zoning or not.

The third advantage is that the model developed using the fuzzy sets theory is enhanced by the a priori knowledge of the expert [13]. Indeed, the expert acts in the selection of the membership functions and in the choice of the aggregation operators. A good knowledge of the system is therefore needed. However, this part of subjectivity can also represent a disadvantage, since two experts may not have the same

opinions and will not make the same choices. This is why it is essential to gather several experts in order to select the membership functions and the aggregation operators with more objectivity [12]. In some cases, a priori knowledge and expertise can be advantageous. Indeed, it can influence the result of the modelling, depending on its final objective, by adding more weight to such or such variable. It should be noticed that certain methods allow to determine the membership degrees more objectively [3, 8].

In conclusion, the fuzzy sets theory and the fuzzy logic can certainly be applied to the field of urban risks, and more particularly to the case of dangerous industries. As previously said, carrying out such a method requires to select input variables and aggregation operators. These choices which will be discussed now.

Variables

We consider that the exposure to dangerous industries E is a function of three variables: the expected effects e , the spatial potential p and the type of accumulation a , as indicated by the following formula (1):

$$E=f(e,p,a) \quad (1)$$

The expected effects of an industrial accident e can be: an explosion, a fire, a leak of toxic products. We think relevant to symbolize that an industry can generate effects of different nature, and that the danger represented by a site on which a fire and an explosion can occur is higher than that the threat of a site only concerned by the fire. This is why three variables are assigned to the expected effects (fig. 3): explosion, fire and leak of toxic products.

The spatial potential p (2) due to an industry is introduced. It can be understood as a gradient of intensity decreasing from the centre of the industry, in opposition to the PPI zoning, which is uniform. This is especially true if we consider that the effects (fire, explosion, leak of polluting and/or harmful products) are not the same close to the source and at the edge of the PPI zoning. In addition, the more numerous the industries are, the higher is the exposure: "the potential p_i produced in a point i by a mass M in a point j is proportional to this mass and inversely proportional to its distance d_{ij} " (translated from Hiegel, [14]).

$$p_i=\alpha\frac{M_j}{d_{ij}} \quad (2)$$

with p_i the potential in i , M_j the mass at the point j , d_{ij} the distance between i and j , α a constant. The mass can be represented as a weight applied to an industry.

The variable resulting from the combination between the three types of effects is called "accumulated expected effects". It symbolizes the accumulation of different effects potentially generated by only one or by two industries, or the accumulation of similar effects generated by two different sites.

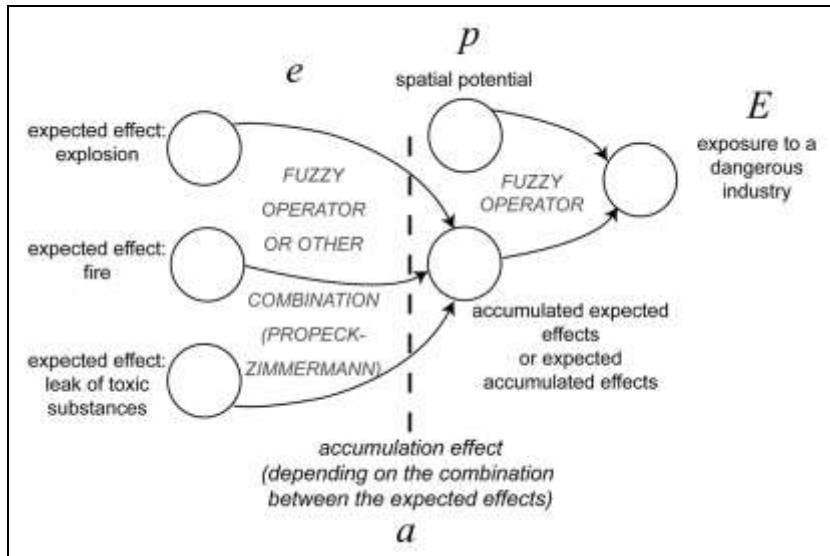


Figure 3: Combination of the different variables, resulting in the evaluation of the exposure to dangerous industries. The accumulation effect can be simple, minor or major, as defined by figure 4.

The type of accumulation a depends on the combination between the effects (fig. 4): it can be simple (only one variable "effect"), minor (two effects produced by two different factories) or major (two different effects generated by the same factory (with probable "domino" effects)). This accumulation effect will be introduced into the model during the choice of the membership degrees.

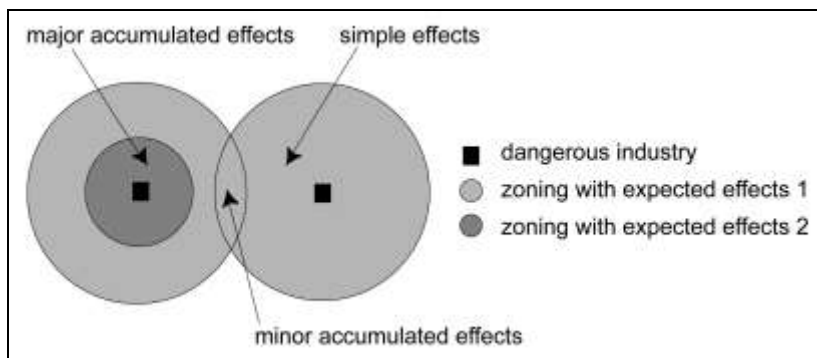


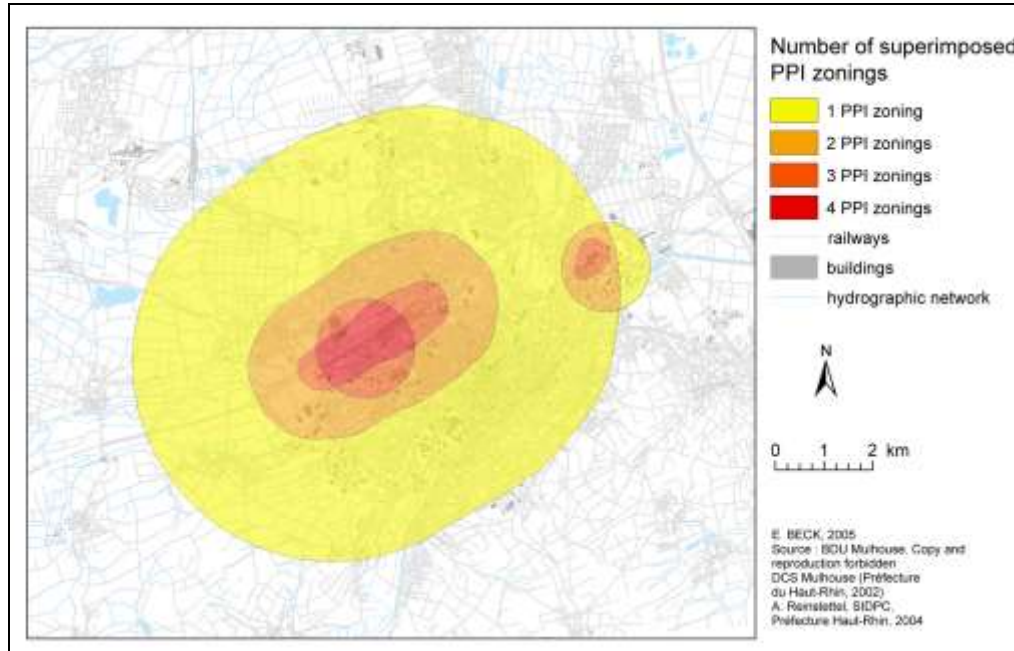
Figure 4: Different types of accumulation depending on the number of sources (one or two industries) and on the type of expected effects (different or similar).

Other variables could have been integrated, like the 3D-shape of the buildings, which would introduce barrier effects, or the proximity of a centre of emergency, which would decrease the exposure. However, our model will not take into account these aspects for the moment.

Fuzzification

Once the variables are chosen, the membership degrees have to be defined. But first of all, we will describe the method that was used to obtain the spatial limits of the accumulated effects. One way could be to generate a map for each expected effect, and then to combine the three variables using the fuzzy sets theory, but we found much more efficient to proceed in another way. We applied the methodology developed by Propeck-Zimmermann [16]. First of all, we only considered the PPI zonings (as they are presently delimited) and not the scenarios zonings (this should be done in a further step). This method

consists in superimposing the different PPI zonings and counting the number of PPI which accumulate on a single point (map 3). If many PPI zonings are superimposed, the exposure is higher.

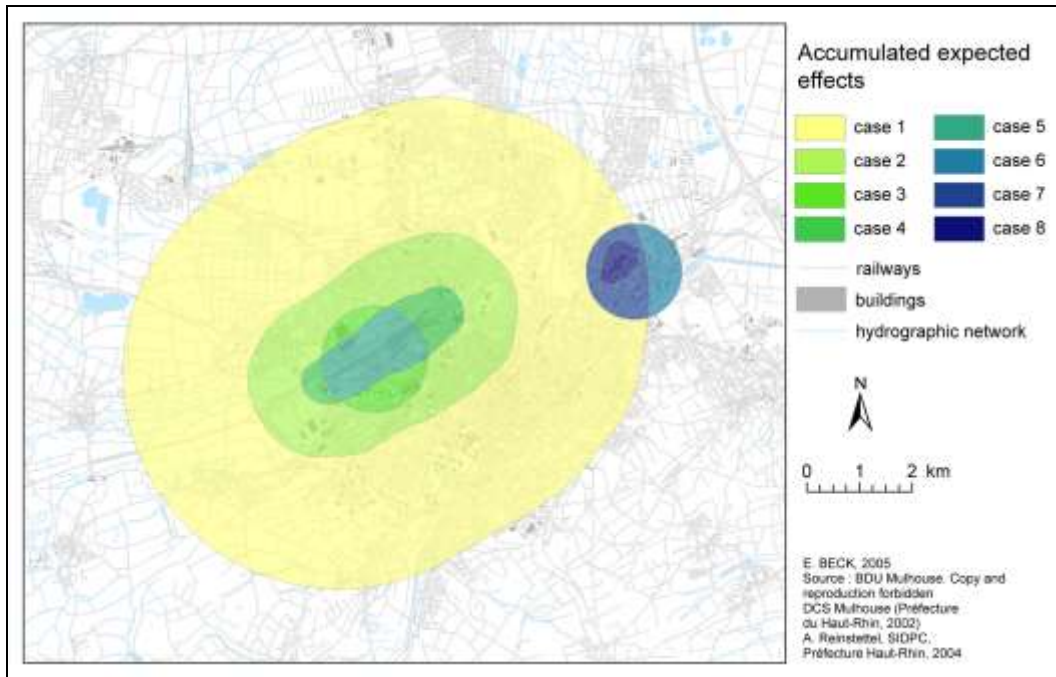


Map 3: Super-imposition of PPI zonings, indicating a higher danger in some areas.

We added an information by characterizing the expected effect for each PPI. Eight combinations of the expected effects can be observed for the region of Mulhouse ("site A, B and C" indicate if the effects are expected for one, two or three different industries):

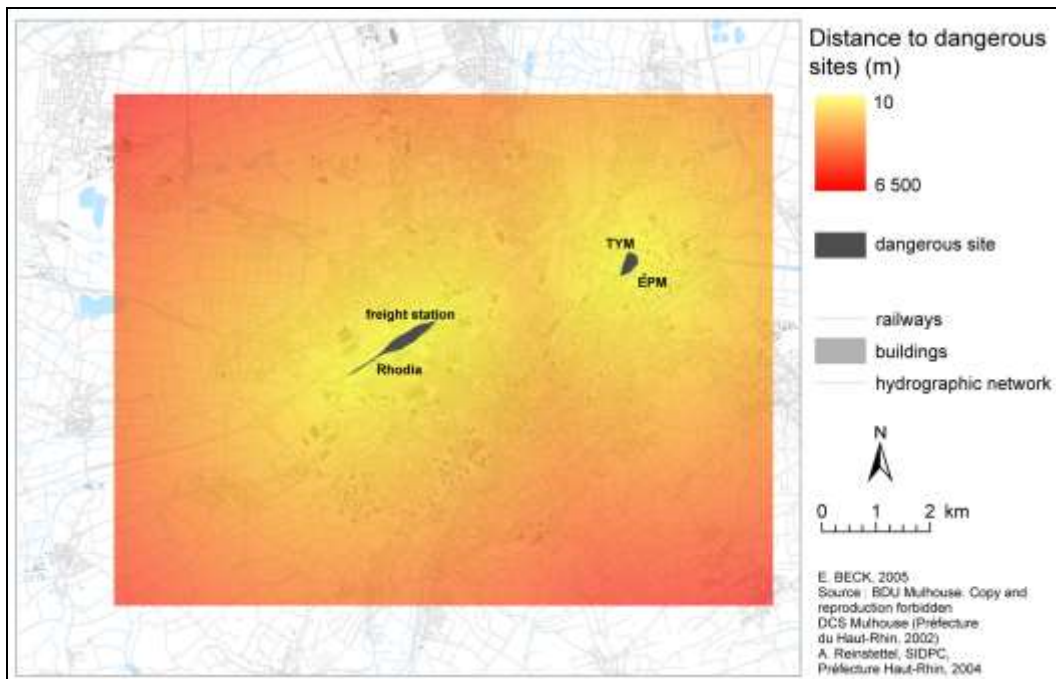
- Case 1: leak of toxic products (site A);
- Case 2: leak of toxic products (site A) + leak of toxic products (site A) (two different toxic products);
- Case 3: leak of toxic products (site A) + leak of toxic products (site A) + leak of toxic products (site B);
- Case 4: explosion (site A) + leak of toxic products (site A) + leak of toxic products (site A);
- Case 5: explosion (site A) + leak of toxic products (site A) + leak of toxic products (site A) + leak of toxic products (site B);
- Case 6: boil over (site A);
- Case 7: boil over (site B) + leak of toxic products (site B);
- Case 8: boil over (site B) + leak of toxic products (site B) + leak of toxic products (site C).

The following map illustrates the eight cases observed.



Map 4: Map of the accumulated expected effects in the urban area of Mulhouse.

Before integrating the potential, we chose to first represent the influence of distance on the exposure to dangerous industries, without taking into account the weight of industries (map 5).



Map 5: Distance to dangerous industries in the urban area of Mulhouse.

We finally retained the membership degrees for each class of the two variables a and p , as described in table 1. Calibration operations will be necessary to validate these choices.

Variable	Classes	Membership degrees
Accumulated expected effects	Case 1: leak of toxic products (site A)	0.1
	Case 2: leak of toxic products (site A) + leak of toxic products (site A)	0.2
	Case 3: leak of toxic products (site A) + leak of toxic products (site A) + leak of toxic products (site B)	0.3
	Case 4: explosion (site A) + leak of toxic products (site A) + leak of toxic products (site A)	0.4
	Case 5: explosion (site A) + leak of toxic products (site A) + leak of toxic products (site A) + leak of toxic products (site B)	0.5
	Case 6: boil over (site A)	0.6
	Case 7: boil over (site B) + leak of toxic products (site B)	0.8
	Case 8: boil over (site B) + leak of toxic products (site B) + leak of toxic products (site C)	1
Distance	5 000 m – 10 m	0 - 1

Table 1: Membership degrees for each fuzzy class of each variable. The membership function assigned to the variable of distance is continuous: the maximum distance of 5 000 m has a membership degree of 0, the distance of 10 m (and less) has a membership degree of 1.

Aggregation Operators

The choice of the operators, which depends on the objective of the research [21], will be done after several simulations, in order to calibrate the model. The choice of the operator will depend on how the different variables should be combined. It seemed significant to represent the increase of the exposure due to the combination of the two variables. Thus, the “fuzzy OR” (3) might not be an appropriate operator, as it only retains the maximum of the two memberships degrees that are combined.

$$\mu_{combination} = \max(\mu_1(x), \mu_2(x) \dots \mu_i(x) \dots \mu_n(x)) \quad (3)$$

where $\mu_{combination}$ and $\mu_i(x)$ represent respectively the membership degree resulting from the combination between the different variables and the membership degree of the element x to the fuzzy class i .

The fuzzy algebraic sum (4) has an increasing effect and allows to represent these cumulative effects. However, this operator is also known as it leads to an over-estimation.

$$\mu_{combination}(x) = 1 - \prod_{i=1}^n (1 - \mu_i(x)) \quad (4)$$

where $\mu_{combination}$ and $\mu_i(x)$ represent respectively the membership degree resulting from the combination between the different variables and the membership degree of the element x to the fuzzy class i .

We could also use the gamma operator (5). It is a good compromise between the increasing effects of the fuzzy sum and the balancing effects of the fuzzy product [4]. It could also be used to represent a cumulative effect of the two variables.

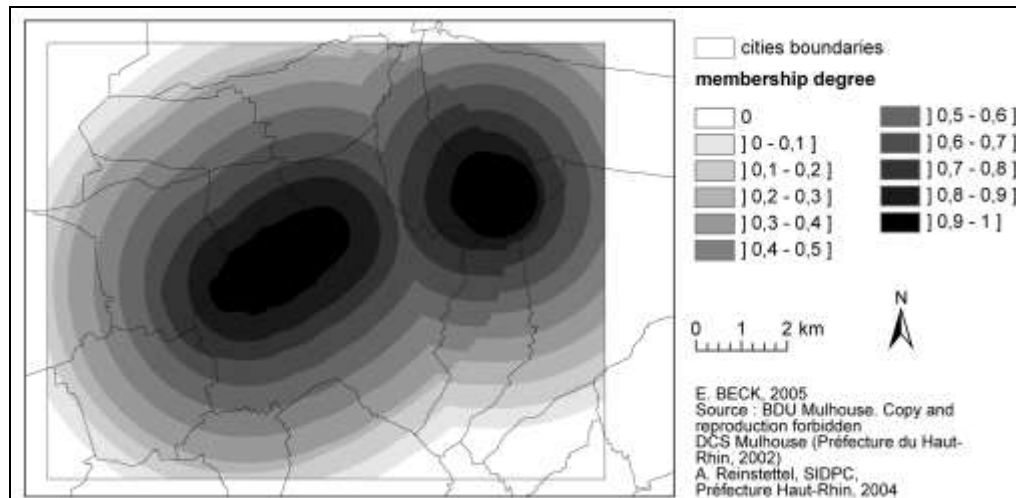
$$\mu_{combination}(x) = \left(\prod_{i=1}^n \mu_i(x) \right)^{1-\gamma} \times \left(1 - \prod_{i=1}^n (1 - \mu_i(x)) \right)^{\gamma} \quad (5)$$

where $\mu_{combination}$ and $\mu_i(x)$ represent respectively the membership degree resulting from the combination between the different variables and the membership degree of the element x to the fuzzy class i , and $0 \leq \gamma \leq 1$.

PRELIMINARY RESULTS

The exposure to a dangerous industry is the result of the combination between the variable of the accumulated expected effects and the variable of distance (the combination with the variable of spatial potential will be done later). Two simulations were done, the first one using the fuzzy sum (map 6), the second one using the gamma operator (with $\gamma = 0.9$, which seems to be the most appropriate [15]) (map 7). The two maps show a higher exposure around the freight station and the TYM and EPM factories, what is due to the superimposition of the PPI zonings as well as the short distance to dangerous sites. The results obtained from the combination of the two variables with the fuzzy sum may be over-estimated, however, this map takes better into account the inverse gradient of exposure due to the distance outside of the PPI zonings. As a matter of fact, the weight of the variable of accumulated effects seems to be overvalued and a membership degree of 0 is assigned to any cell located out of the PPI zonings.

These preliminary results tend to show that the fuzzy sum may be more adapted to our study. Further investigations need to be done, in order to integrate the weight of the factories (and the influence of two near factories) by the way of the spatial potential.



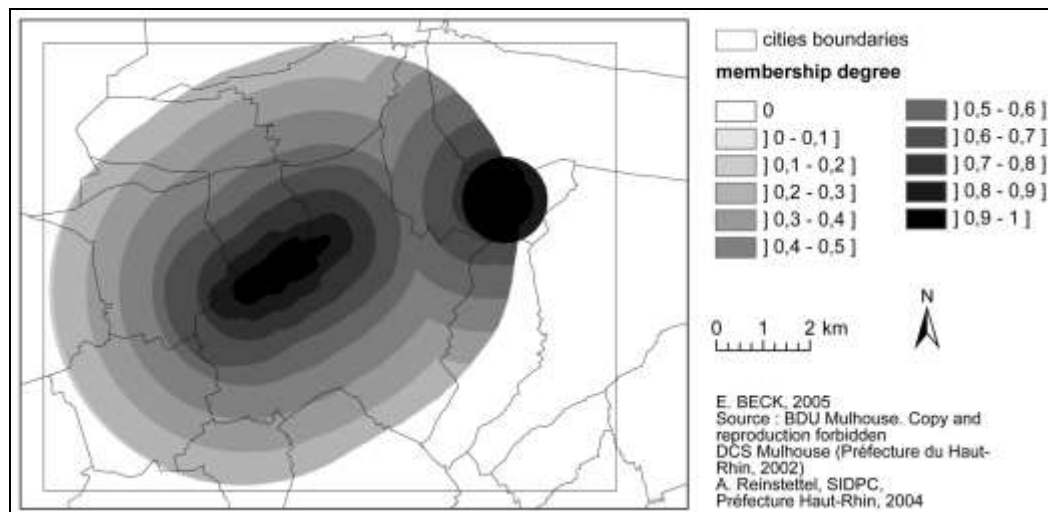
Map 6: map of exposure to dangerous industries in Mulhouse obtained with the fuzzy sum. A membership degree of 1 represents a high exposure.

CONCLUSION AND FURTHER DEVELOPMENTS

In this paper, we have presented a study realized in the framework of a global research, which aims at evaluating the consequences of an earthquake on an urban area, and particularly on the dangerous industries. The paper has introduced a methodology of evaluation of the exposure to dangerous industries. It has been applied on the urban area of Mulhouse, which is characterized by four dangerous sites (three "Seveso" sites and a freight station). We chose to use the fuzzy sets theory, as it provides very interesting advantages to the study of risks in general. Two variables have been considered: the accumulated expected effects and the spatial potential of dangerous industries. These variables have been retained in order to illustrate that the exposure is higher when several industries are close together. We have also used the potential in order to point out that the effects of an industry are greater at a short distance than very far from it. The variables have been combined with two aggregation operators, the fuzzy sum and the

gamma operator. The first simulations show that two sites are more exposed to dangerous sites (close to the freight station and near the TYM and EPM factories). The integration of the distance (or the spatial potential) into the model allows to define gradients of exposure inversely proportional to the distance to dangerous industries. The fuzzy sum seems to be more adapted to our study than the gamma operator.

The further step will consist in combining the layer of exposure to dangerous industries with the layer of the vulnerable elements, in order to obtain a map of the industrial risk. Then, we will combine the map of industrial risk with the map of seismic risk, in order to identify the areas of combined and accumulated risks, i.e. the areas of greatest danger. These maps could be worth it for the authorities who are in charge of the management of risks.



Map 7: map of exposure to dangerous industries in Mulhouse obtained with the gamma operator. A membership degree of 1 represents a high exposure.

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