The application of fuzzy logic to the precautionary principle

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Abstract

One of the major problems in the implementation of the precautionary principle in environmental cases is the estimation of the weight of evidence. In this paper we propose a formal method that determines the weight of evidence based on the specific parameters of a given case. The proposed method is based on an artificial intelligence approach called *fuzzy logic*, which is commonly used as an interface between logic and human perception, and often applied to computer-based complex decision making. We use one fuzzy expert system that provides a quantification of the estimated environmental damage, and a second fuzzy expert system that computes the weight of evidence in a given case. The proposed expert system can be easily defined and adjusted by regulators and environmental science and policy experts.

1 Introduction

Precaution is a principle that provides an intuitively simple approach to ensuring that human intervention in environmental systems is made less damaging (Wiener & Roger, 2002). The precautionary principle has been previously cast as the guiding principle which ”... ensures that a substance or activity posing a threat to the environment is prevented from adversely affecting the environment, even if there is no conclusive scientific proof linking that particular substance or activity to environmental damage” (Cameron & Abouchar, 1991). The 1992 United Nations Conference on Environment and Development provided compelling evidence for the above statement ”...Where there are threats of serious or irreversible damage, lack of scientific certainty shall not be used as a reason for postponing cost effective measures to prevent environmental degradation" (United Nation Conference on Environment and Development, 1992).

The use of the precautionary principle in international environmental agreements has experienced tremendous growth since 1980 (Woolcock, 2002). The precautionary principle can be also found in the roles governing international trade, such as the Cartagena Protocol on Biosafety (Cartagena Protocol on Biosafety, 1995). In addition, the precautionary principle is increasingly being involved at the national level (Hunter, Salzman & Zaelke, 2001). Therefore, it seems reasonable to say that this principle has been raised to a level of general principle due to its acceptance in many legal areas, including environmental law.

The precautionary principle has a wide spectrum in terms of "strong" and "weak" versions of it (Wiener & Roger, 2002; Tinckner, 1996). The implementation of the precautionary principle in its *strong* version requires demonstrating that a specific risky activity poses no risk to the environment. In other words, the proponent of the risky activity has to prove beyond all reasonable doubt that it poses no risk. However, the implementation of the precautionary principle, as articulated in the 1992 Rio Declaration on Environment and Development (United Nation Conference on Environment and Development, 1992), raises several questions, such as what is "serious or irreversible damage"? How much and what kind of uncertainty? How can the term be applied to different scientific areas? However, the most problematic question is what evidential burden is needed before taking action to protect the environment and public health.

In this paper we propose a new fuzzy logic-based method for determining the weight of evidence required in the implementation of the precautionary principle in different environmental cases. In Section 2 we discuss the weight of evidence and its role in the implementation of the precautionary principle, in Section 3 we briefly describe fuzzy logic, in Section 4 the application of fuzzy logic to the precautionary principle is presented, in Section 5 we describe a fuzzy logic based evaluation of environmental damage, and in Section 6 we present an example using real-life data of an environmental case.

2 Weight of evidence in the precautionary principle

All activities involve risk, which combines the likelihood and the harm resulting from exposure to an activity. Uncertainty can be distinguished from probability (Wiener & Roger, 2002). While some risks are well understood, others are highly uncertain. For instance, death by cellular phone radiation and lightning strikes may both be of low probability, but the former may be far more uncertain because we are unsure whether cellular phones even cause brain tumors. Obviously, all risks are uncertain to some extent, because we can never know the future with complete certainty. Science is accustomed to this uncertainty. In the face of uncertainty about risk, precautionary measures are often taken.

Admittedly, precaution lacks a specific definition. The precautionary principle has a wide spectrum in terms of "strong" and "weak" versions of it. At its strongest version, the precautionary principle may be interpreted to prohibit all activities in certain ecosystems, while at its weakest version the principle provides the authority to consider other factors than environmental risk (Tinckner, 1996; Soule, 2000). Although there is no clear definition to the precautionary principle, it has been cast as the guiding principle ”... Where there are threats of serious or irreversible damage, lack of scientific certainty shall not be used as a reason for postponing cost effective measures to prevent environmental degradation” (United Nation Conference on Environment and Development, 1992). This wording can be found in international and domestic legislations such as the preamble of the Canadian Environmental protection Act (1999).

At the precautionary principle strongest version, it is clear when the principle applies. All activities are prohibited until it is proven that there is no harm to the environment and public health. In addition, it requires in some cases shifting the burden and standard of proof, which means that uncertain risk requires forbidding the potentially risky activity until the proponent of the activity demonstrate that it poses no risk. For example, United States improved pesticide regulation and uses the precautionary principle in its strong version in the Food Quality Protection Act by shifting the burden of proof to the manufactures. According to the act, all pesticide residues must demonstrate ”a reasonable certainty of no harm” if they are permitted in food products (Rosenbaum, 2002).

In between the two extreme versions, each version of the precautionary principle has the known prescription that scientific certainty is not required before taking preventive measures. These versions are often similar in form and substance, yet they contain minor wording differences with potentially major policy implications. Swedish philosopher Per Sandin proposed 19 versions of the precautionary principle. He found substantial variation along each of four dimensions, which he characterized as threat, uncertainty, action and command (Sandin, 1999). For instance, different versions of the precautionary principle vary along the threat dimension, which defines the degree of threat necessary to trigger the principle from ”threats of serious and irreversible damage” to ”possible risks” (Marchant & Mossman, 2005).

No version of the precautionary principle in between the two extreme versions is clear on when the principle applies. In this paper we consider the version of the precautionary principle offered by the United Nations (United Nation Conference on Environment and Development, 1992), which raises several questions. According to this version, the principle is triggered ”where there are threats of serious or irreversible damage”. However, the term ”serious or irreversible damage” is not defined. More specifically, it also does not specify how far in the future we need to look in order to determine ”irreversible damage”. Another issue is the strength of evidence required to establish ”serious or irreversible damage”.

Since there is no clear definition to ”serious or irreversible damage”, the implementation of the precautionary principle becomes entirely arbitrary. For example, the European Union advocates application of the precautionary principle to genetically modified (GM) food. However, it does not apply the principle to organic food or natural dietary supplements, which unlike GM foods, are responsible for many documented cases of illness and death (McHughen, 2000). Moreover, some countries in the EU, such as France and Italy, that have adopted restrictive policies on GM foods based on the precautionary principle do not apply the principle to restrict economically important activities such as tourism, even though it causes more damage to the natural environment of those countries than GM foods (Marchant & Mossman, 2005).

Nowadays we can also find other examples of the arbitrary application of the precautionary principle. One example is the government of Norway, which recently banned Kellogg's Corn Flakes fortified with vitamins because "the fortification in question might be a health hazard when eaten in uncontrollable and unforeseen amounts" (Case E– 3/00, 2001). Another example is France, that recently employed the precautionary principle to ban the caffeinated energy drink *Red Bull* based on a paternalistic concern that its citizens, in particular pregnant women, would consume too much caffeine (Case C– 24/00, 2004). Furthermore, courts can use the precautionary principle to reach questionable results. One such example is the decision of an Australian court to prohibit, based on the precautionary principle, a town from building an important bridge because of its potential effect on the endangered giant burrowing frog (Case No. 10376.81, 1993). The problem was that the giant burrowing frog had never been seen anywhere near the proposed bridge, having been observed several kilometers away on only two occasions some twenty years earlier, and on another occasion allegedly heard near the bridge site (Marchant & Mossman, 2005). Therefore, without objective criteria limiting when the precautionary principle applies and what it requires, the potential reach and force of the precautionary principle are boundless, restrained only by arbitrary political vagaries.

It is well agreed by practically all-legal systems that there is no such thing as absolute proof. Instead, relative standards are used. In criminal law, the legal system uses the standard of proof of beyond all reasonable doubt (probability of 0.99), while in civil law it uses the balance of probabilities (probability of 0.51). Demand for absolute proof of safety or harm is impossible. Nevertheless, the UK government required proof "without possible doubt" in a test case on eutrophication in the Ythan estuary (MacGarvin, 2001; Anon, 1997). There is a wide range in the evidential burden demanded by regulators before taking action to protect the environment and public health. This ranges from proof without doubt as the above Ythan case, down to very low levels of evidence, such as the United States precautionary principle bans related to the mad cow disease (MacGarvin, 2001).

It is easy to determine the weight of evidence at the two ends of the spectrum version of the precautionary principle. At its strongest version, one needs to prove beyond reasonable doubt that the activity is safe to the ecosystems. On the other side of the spectrum, at its weakest version, there is no need to prove any causation between the activity and the damage to the environment before applying the precautionary principle. The problem starts to evolve when we look at the versions in between the spectrum. Previously proposed formal approaches applied fuzzy logic to the law of evidence (Shapira, 2000), and some applications of fuzzy logic to the ancient Biblical legal system have also been proposed (Shapira, 1999). In this paper we propose to apply fuzzy logic to the most cited version of the precautionary principle, which is the one defined in principle 15 of the 1992 Rio Declaration on Environment and Development: "Where there are threats of serious or irreversible damage, lack of scientific certainty shall not be used as a reason for postponing cost effective measures to prevent environmental degradation" (United Nation Conference on Environment and Development, 1992). This mathematical method will help decision makers to determine the weight of evidence that is needed in order to take precautionary actions.

In many legal disciplines, the evaluation of the weight of evidence involves many parameters that cannot be effectively quantified and processed by a mathematical model. For instance, determining the best interest of the child depends heavily on the impression of the judge from the parties claiming for child custody, and many other factors that involves human behavior that might not be easily quantified. In criminal cases the judge might also want to consider very many parameters before making a decision. These parameters are not well-defined and cannot be easily quantified due to the complex nature of human behavior and personality. Moreover, the absence of human judgment in cases that involves human behavior (such as criminal cases) might introduce moral issues that will strongly counter the use of expert systems in court decisions.

Environmental cases, on the other hand, are usually more technical. The parties in these cases are usually a corporation vs. the local government, and the human factor plays a smaller role comparing to other legal disciplines. This nature of environmental cases makes them suitable for using expert systems designed by regulators and environmental experts. The use of these systems can assist courts in making decisions in this technical field that is sometimes beyond their field of expertise, and will provide objective decisions that will be less influenced by the knowledge and the personal point of view of the specific court.

3 Fuzzy logic

Fuzzy logic (Zadeh, 1965, 1988) is an extension of Boolean logic that is often used for computer-based complex decision making. While in classical Boolean logic an element can be either a full member or non-member of a Boolean (sometimes called ”crisp”) set, the membership of an element to a fuzzy set can be any value within the interval $[0, 1]$, allowing also partial membership of an element in a set.

A fuzzy expert system consists of three different types of entities: fuzzy sets, fuzzy variables and fuzzy rules. The membership of a fuzzy variable in a fuzzy set is determined by a function that produces values within the interval [0,1]. These functions are called *membership functions*. Fuzzy variables are divided into two groups: *antecedent variables*, that are assigned with the input data of the fuzzy expert system, and *consequent variables*, that are assigned with the results computed by the system.

The fuzzy rules determine the link between the antecedent and the consequent fuzzy variables, and are often defined using natural language linguistic terms. For instance, a fuzzy rule can be ”if the temperature is cold and the wind is strong then wear warm clothes”, where *temperature* and *wind* are antecedent fuzzy variables, *wear* is a consequent fuzzy variable and *cold*, *light* and *warm clothes* are fuzzy sets. The use of linguistic terms makes fuzzy logic a common approach that is used for compiling human perception-based decision making into formal mathematical models (Zadeh, 2002).

The process of a fuzzy system has three steps. These steps are *Fuzzification*, *Rule Evaluation*, and *Defuzzification*. In the fuzzification step, the input crisp values are transformed into degrees of membership in the fuzzy sets. The degree of membership of each crisp value in each fuzzy set is determined by plugging the value into the membership function associated with the fuzzy set.

In the rule evaluation step, each fuzzy rule is assigned with a strength value. The strength is determined by the degrees of memberships of the crisp input values in the fuzzy sets of antecedent part of the fuzzy rule. Two commonly used rule evaluation methods are *min*, which assigns the strength with the minimum degree of membership among the fuzzy sets of the rule, and *product*, which assigns the strength with the product of all degrees of membership.

The defuzzification stage transposes the fuzzy outputs into crisp values. While there are variety of defuzzification methods, in this work we used the popular *center of mass* (Mamdani & Assilian, 1975) approach, which calculates the output crisp values based on the mass center of the membership functions of the consequent fuzzy variable. A detailed example of how *center of mass* defuzzification is used is given in Section 6.

4 The application of fuzzy logic to the precautionary principle

A fuzzy expert system can determine the weight of evidence in environmental cases based on several objective parameters. This approach can solve one of the major problems in the implementation of the precautionary principle, which is the difficulty to determine the weight of evidence for each environmental case (Miller & Conko, 2000), as explained in Section 2. Since defining the fuzzy sets and fuzzy rules of a fuzzy expert system is done by using linguistic terms, such a system can be defined by regulators and environmental science, law and policy experts. Implementation of such a system will probably trigger debates between different concepts and approaches to environmental issues introduced by different experts, who will have to reach an agreement about how evidence should be weighted in environmental cases. However, once the fuzzy expert system is defined, all courts can use the same system, so that the weight of evidence is quantified in an objective and non-arbitrary fashion that has a minimal dependency on the point of view of the specific person or court making the decisions. The way such an expert system is defined is described in this section.

Although several different methods of building fuzzy expert systems have been proposed and used (Hwang, 1999; Maeda, et al., 1991; Masuoka, Watanabe & Kawamura, 1990; Funabashi et al., 1995), the fuzzy expert system proposed in this paper is based on the traditional max/min approach introduced by (Zadeh, 1983, 1988). More information regarding building and using fuzzy expert systems can be found in (Siler & Buckley, 2004; Kandel, 1992; Schneider et al., 1996).

4.1 Fuzzy variables

The fuzzy expert system determines the weight of evidence as a function of four parameters. Each parameter is an antecedent fuzzy variable as follows:

1. Damage - The potential worst-case scenario damage caused by the action discussed in the given case. In the expert system described in this section, *Damage* has four crisp sets *Small*, *Medium*, *Substantial* and *Critical*. In Section 5 we describe a fuzzy expert system that provides a formal method that determines the value of this variable.

2. Time: The time required for the damage to take effect. The domain of this fuzzy

variable is the interval (0,∞).
3. Likelihood: The likelihood that the damage will indeed be caused. The domain of this variable is the interval [0,1].
4. Evidence: The accuracy of the evidence. The value of this variable is determined by the quality and accuracy of the existing knowledge of the experts estimating the values of the three variables described above. This variable is required since in many cases the effect on the environment cannot be accurately determined, and the knowledge required for accurate estimations is not always available.

Although some of these values might be determined in a somewhat subjective fashion, environmental experts are usually able to handle them based on existing literature. In the case of a debate, the arguments will be based on existing literature and current scientific knowledge, rather than on an arbitrary decision as is often the case in environmental cases, which is a well-known problem in environmental law as described in Section 2.

Damage is a crisp variable, and therefore no fuzzy sets are defined for this variable. The fuzzy variable *Time* uses the three fuzzy sets *Immediate*, *Short* and *Long*, as described in Figure 1.

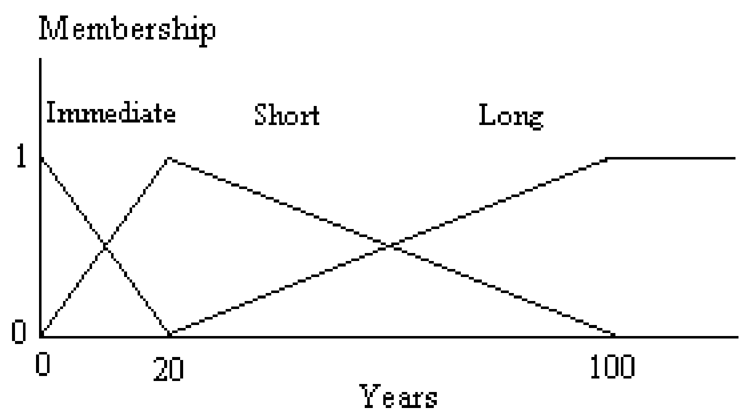

Figure 1: Fuzzy sets defined for the antecedent fuzzy variable *Time*

The fuzzy variable *Likelihood* uses the three fuzzy sets *Low*, *Medium* and *High*, as described in Figure 2.

The fuzzy variable *Evidence* uses the three fuzzy sets *Weak*, *Fair* and *Strong*, as described in Figure 3.

An example of the use of this parameter can be a case in which studies suggest that a certain action has a probability of 0.5 to cause critical damage on the short term. This information can be used as a strong evidence for the analysis of an identical case, but if the new case is similar, but not identical, then the evidence can be used with a lower level of reliability.

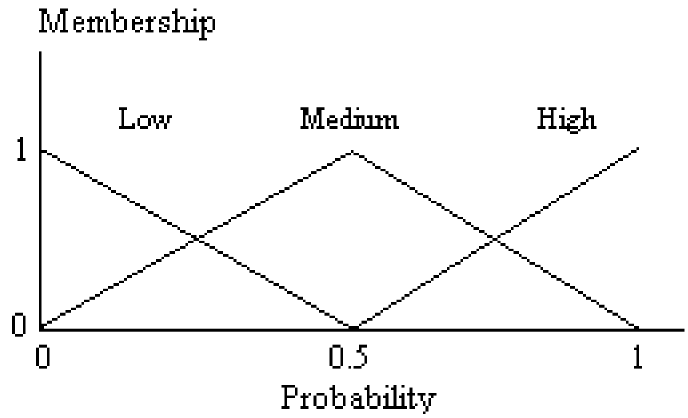

Figure 2: Fuzzy sets defined for the antecedent fuzzy variable *Likelihood*

The consequent fuzzy variable *Weight* uses the three fuzzy sets *Weak*, *Balanced* and *BARD* (beyond all reasonable doubt), as described in Figure 4.

4.2 Fuzzy rules

The fuzzy rules are defined using the fuzzy sets described in Section 4.1, and are based on an intuitive estimation of the weight of evidence. Since the expert system described in this paper defines four sets for *Damage*, three sets for *Time*, three sets for *Likelihood* and three sets for *Evidence*, the total number of fuzzy rules required for the expert system is $4 \times 3 \times 3 \times 3 = 108$. The rules are defined using the estimated weight of evidence needed for each case. For instance, a fuzzy rule can be defined as:

Critical, Immediate, High, Strong $\longmapsto$ BARD

The rule means that if the potential damage is critical, the damage effect is immediate, the likelihood of the damage is high and the evidence is strong, then the acting person or organization has to prove beyond all reasonable doubt that their activity is safe. Another example is the rule:

Medium, Long, Low, Medium $\longmapsto$ Weak

The intuition of this rule is that if there is a low probability that medium damage will be caused on the long term, and the reliability of this estimation is medium, then it will be sufficient for the acting person or organization to provide weak evidence that the activity is safe. Some of the other rules could be the following:

Medium, Short, Low, Strong $\mapsto$ Weak
Medium, Short, Low, Fair $\mapsto$ Weak

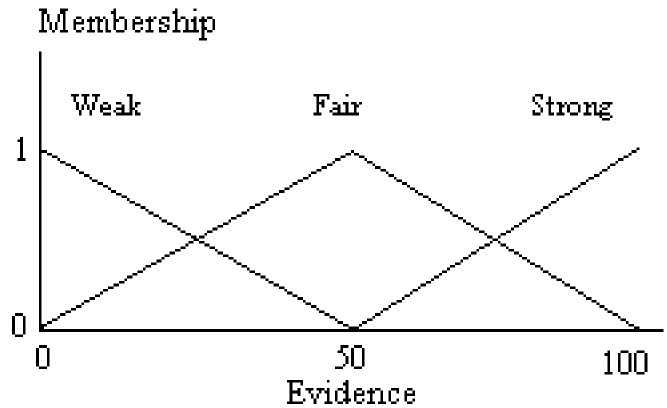

Figure 3: Fuzzy sets defined for the antecedent fuzzy variable *Evidence*

Medium, Short, High, Fair ↦ Balanced
Medium, Short, High, Strong ↦ Balanced
Medium, Immediate, High, Strong ↦ BARD
Medium, Immediate, High, Weak ↦ Balanced
Substantial, Long, Low, Strong ↦ Weak
Substantial, Long, Low, Fair ↦ Weak
Substantial, Long, Low, Weak ↦ Balanced
Substantial, Long, Medium, Strong ↦ Balanced
Substantial, Long, Medium, Fair ↦ Balanced
Substantial, Long, Medium, Weak ↦ Balanced
Substantial, Long, High, Strong ↦ BARD
Substantial, Long, High, Fair ↦ BARD
Substantial, Long, High, Weak ↦ Balanced
Substantial, Short, Low, Strong ↦ Balanced
Substantial, Short, Low, Fair ↦ Balanced
Substantial, Short, Low, Weak ↦ Balanced
Substantial, Short, Medium, Strong ↦ BARD
Substantial, Short, Medium, Fair ↦ Balanced
Substantial, Short, Medium, Weak ↦ Balanced
Substantial, Short, High, Strong ↦ BARD
Substantial, Short, High, Fair ↦ BARD
Substantial, Short, High, Weak ↦ Balanced
Substantial, Immediate, Low, Strong ↦ Balanced
Substantial, Immediate, Low, Fair ↦ Balanced
Substantial, Immediate, Low, Weak ↦ Balanced
Substantial, Immediate, Medium, Strong ↦ BARD
Critical, Long, Low, Strong ↦ Balanced
Critical, Long, Low, Fair ↦ Balanced

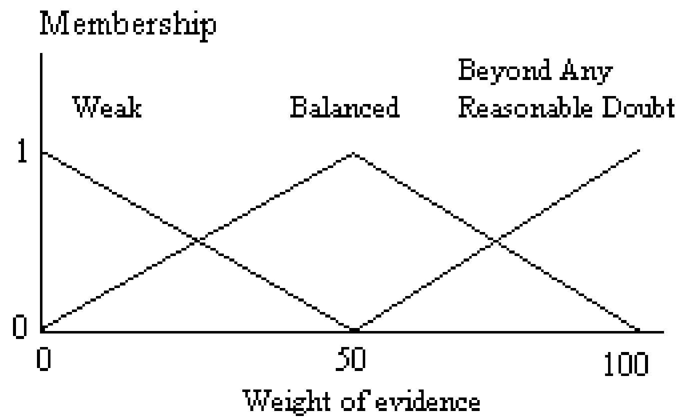

Figure 4: Fuzzy sets defined for the consequent fuzzy variable *Weight*

Critical, Long, Low, Weak $\mapsto$ Balanced
Critical, Long, Medium, Strong $\mapsto$ Balanced

Obviously, these rules are subjective, and can be easily changed according to the reasoning of any given legal system. Once the expert system is defined, the weight of evidence in any given case can be computed using the fuzzy expert system. While the variable that has the strongest effect on the result is *Damage*, the value of this variable is determined in a subjective fashion. In Section 5 we describe a formal method for evaluating the membership of *Damage* using objective parameters.

4.3 The computation process

The computation process can be described best by an example. Suppose that the damage is defined as *substantial*, and there is a probability of 0.75 that it will take 40 years for the damage to take effect. In a scale of 0 to 100, the reliability of this estimation is 90.

The fuzzification of the probability 0.75 using the membership functions described in Figure 2 provides that the membership of 0.75 in the fuzzy set *Medium* is 0.5, and the membership in the fuzzy set *High* is also 0.5. The membership in the fuzzy set *Low* is 0. Based on the membership functions described in Figure 1, the value 40 has a membership of 0.75 in the fuzzy set *Short* and membership of 0.25 in the fuzzy set *Long*. Using the membership functions described in Figure 3, the value 90 is fuzzified so that its membership in the fuzzy set *Fair* is 0.2, and in the fuzzy set *Strong* its membership is 0.8.

The inference computation assigns each fuzzy rule with the minimum membership value. For instance, in the fuzzy rule *Substantial, Short, Medium, Fair* $\mapsto$ *Balanced*, the membership of *substantial* in the crisp set *Substantial* is 1, the membership in the fuzzy set *Short* is 0.75, the membership in the fuzzy set *Medium* is 0.5 and the membership in the fuzzy set *Fair* is 0.2. Since the minimum of these values is 0.2, the strength of the fuzzy rule is set to 0.2.

In our example, the rules with strength greater than zero are:

Substantial, Long, Medium, Strong $\mapsto$ Balanced (0.25)
Substantial, Long, Medium, Fair $\mapsto$ Balanced (0.2)
Substantial, Long, High, Strong $\mapsto$ BARD (0.25)
Substantial, Long, High, Fair $\mapsto$ BARD (0.2)
Substantial, Short, Medium, Strong $\mapsto$ BARD (0.5)
Substantial, Short, Medium, Fair $\mapsto$ Balanced (0.2)
Substantial, Short, High, Strong $\mapsto$ BARD (0.5)
Substantial, Short, High, Fair $\mapsto$ BARD (0.2)

The fuzzy rules are grouped by their consequent part, and each group is assigned with the value of the fuzzy rule that its value is maximal among all other rules in the group. In our example, all fuzzy rules with the consequent part *Weak* are assigned with the value *0*, so that the value assigned to that group is *0*. Among all fuzzy rules with the consequent part *Balanced*, the maximum value is 0.25, and among the fuzzy rules with the consequent part *BARD* the maximum value is 0.5.

The defuzzification is based on *center of mass* (Mamdani & Assilian, 1975; Zadeh, 1988). Therefore, the value of the consequent variable is determined by the mass center of the area of the membership functions of the consequent variable as described in Figure 5.

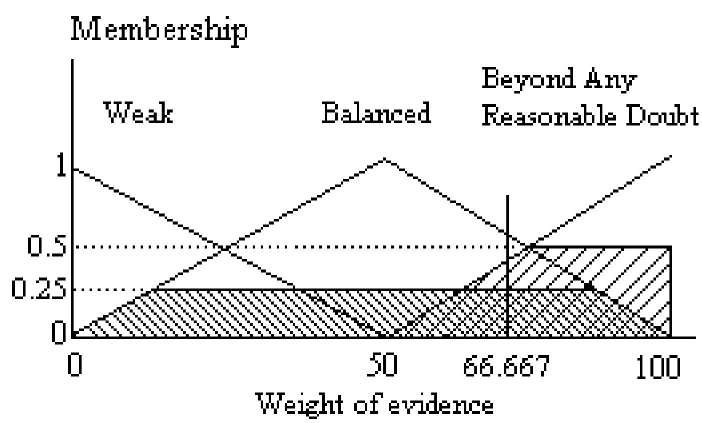

Figure 5: *Center of mass* defuzzification. The mass center (the point at which the colored area to its left is equal to the colored area to its right) in this case is at 66.667

The value of the consequent variable is determined by the mass center of the colored area in Figure 5. The membership functions are colored based on the maximal strength among all fuzzy rules that have that membership function as consequent part. The mass center of the colored area (the point at which the colored area to its left is equal to the colored area to its right) is the value assigned to the consequent variable. In this example, the mass center is around 66.667. That means that the weight of evidence in the case of this example should be around 70% (the exact value 66.667 can be safely rounded to 70 since in legal cases it is often not practical to weight the evidence in a precise fashion).

4.4 Multiple scenarios

In many practical environmental cases, several scenarios are proposed for the same case. For instance, the analysis of a single case can provide two possible scenarios: The first predicts a medium damage on the short term, and the second suggests that critical damage will take effect on the long term. Another example could be different reliability of the estimations. One estimation can be based on strong evidence predicting small damage on the long term, but the other might provide weak evidence that a substantial damage will be caused on the short term.

In order to deal with multiples scenario, we suggest to use the fuzzy expert system described above with the parameters of all proposed scenarios. The weight of evidence for the case is given in Equation 1.

$$\max_i(F_i) \tag{1}$$

Where F_i is the weight of evidence of scenario *i*, as computed by the fuzzy expert system. That is, the weight of evidence of the case is simply the maximum weight of evidence among all tested scenarios.

5 A fuzzy logic-based evaluation of environmental damage

The most arbitrary part in the fuzzy expert system described in Section 4 is the estimation of the damage. That is, without a defined criteria, what seems *critical damage* to one court might be evaluated as *medium* damage by another. Therefore, a formal model that determines the scope of the damage is required. We propose to estimate the damage using a fuzzy expert system. The results provided by the expert system can be used as the membership of the antecedent variable *Damage* (of the model described in Section 4) in the sets *Small*, *Medium*, *Substantial* and *Critical*.

The damage is estimated based on three antecedent fuzzy variables: The effect of the damage, the number of individuals affected by the damage, and the time it would take to repair the damage. The first variable, *Effect*, is the effect of the damage, and has the four crisp sets *death*, *lethal disease*, *disease* and *wildlife death*.

The second variable, *Individuals*, is the number of individuals expected to be affected by the damage, and has five fuzzy sets *None*, *Few*, *Town-scale*, *Country-scale* and *Global*, as described in Figure 6.

The third fuzzy variable, *Repair*, defines the time it would take to repair the damage, and has four fuzzy sets, *Short*, *Medium*, *Long* and *Irreversible*, as described in Figure 7.

The fuzzy rules are based on the crisp and fuzzy sets described above, and can be the following:

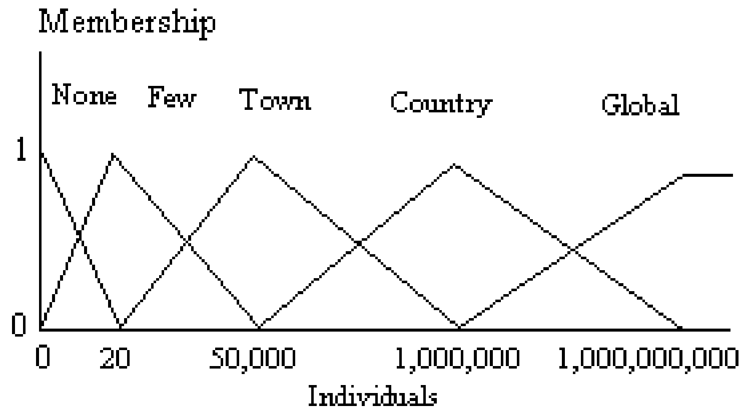

Figure 6: Fuzzy sets defined for the antecedent fuzzy variable *Individuals*

Death, Town, Long $\mapsto$ Critical
Death, Town, Irreversible $\mapsto$ Critical
Disease, Few, Long $\mapsto$ Medium
Disease, Town, Long $\mapsto$ Substantial
Disease, Country, Long $\mapsto$ Critical
Wildlife, Few, Short $\mapsto$ Small
Wildlife, Few, Medium $\mapsto$ Small
Wildlife, Few, Long $\mapsto$ Small
Wildlife, Few, Irreversible $\mapsto$ Medium
Wildlife, Town, Short $\mapsto$ Small
Wildlife, Town, Medium $\mapsto$ Medium
Wildlife, Town, Long $\mapsto$ Medium
Wildlife, Town, Irreversible $\mapsto$ Substantial
Wildlife, Country, Short $\mapsto$ Substantial
Wildlife, Country, Medium $\mapsto$ Substantial
Wildlife, Country, Long $\mapsto$ Critical
Wildlife, Country, Irreversible $\mapsto$ Critical

Obviously, in this paper we present only the formal methodology of the estimation of the weight of evidence. The fuzzy rules and fuzzy sets described above can be modified and adjusted to the specific reasoning of any legal system.

The computation process can be best described by an example. Suppose we evaluate the potential damage of an oil spill near the coast of Alaska, based on the Exxon Valdez incident on March 24, 1989 (EPA, 1989; Alaska Oil Spill Commission, 1990). The Exxon Valdez oil spill was the direct cause of the death of some 500,000 birds and mammals (Spies et al., 1996). Therefore, when computing the estimated damage using the proposed fuzzy expert system, the membership of the antecedent variable *Effect* in

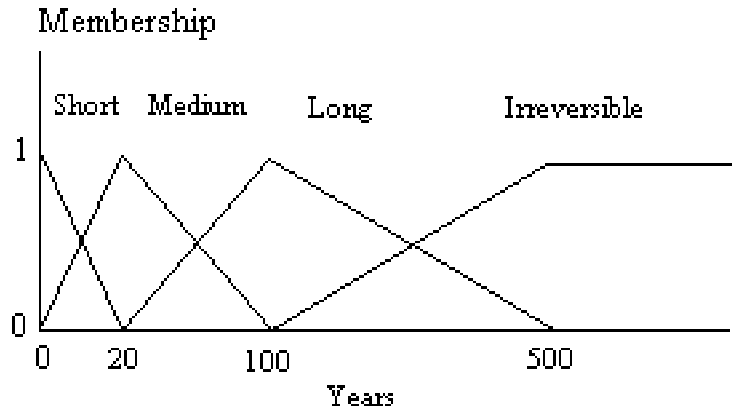

Figure 7: Fuzzy sets defined for the antecedent fuzzy variable *Repair*

the set *Wildlife* is 1, and the membership of the fuzzy variable *Individuals* in the fuzzy sets *Town* and *Country* are 0.53 and 0.47 respectively. The estimated recovery time is 30 years (Peterson et al., 2003). The fuzzification of the value *30* using the membership functions described in Figure 7 provides membership of 0.875 in the fuzzy set *Medium* and 0.125 in the fuzzy set *Long*.

The rule evaluation assigns a positive strength only to rules that include the crisp set *Wildlife*. The strengths of the last eight rules listed above are 0, 0.53, 0.125, 0, 0, 0.47, 0.125, 0. Among all fuzzy rules with the consequent part *Medium*, the maximal rule strength is 0.53. Among the rules with consequent parts *Substantial* and *Critical*, the maximal strengths are 0.47 and 0.125 respectively. These values can be used by the expert system described in Section 4 as the membership values of the antecedent variable *Damage*, such that the membership in the fuzzy set *Medium* is 0.53, the membership in the fuzzy set *Substantial* is 0.47 and the membership in the fuzzy set *Critical* is 0.125. This provides a smoother and more formal evaluation of the damage, rather than selecting an arbitrary value from a discrete set of four elements.

6 Example Application to Real-life Data

In order to demonstrate how the proposed fuzzy expert system is applied we chose to use it for calculating the weight of evidence using real-life data. The environmental issue that was chosen for this purpose is the protection of the sturgeon population in the Muskegon River. Overfishing and pollution are considered as the primary reasons of the sturgeon population decline in the Muskegon river, which decreased from about 1.5 millions in the 1800s to less than 5000 in 2005 (Zollweg et al., 2004). If overfishing and pollution continues, the remaining 5000 long-living fish will become extinct in $\sim$15 years.

According to the proposed fuzzy expert system, the first step is estimating the environmental damage. This can be done by using the fuzzy expert system described in Section 5, where the number of *individuals* expected to be affected by the damage is 5000, the *effect* of the damage is *wildlife death*, and the damage is *irreversible*, due to previous cases that introduced significant difficulties in recovering fish population (Bronte et al., 2006).

The value of the antecedent variable *Individuals* is 5000, and based on the membership functions described in Figure 6, the degree of memberships in the fuzzy sets *Few* and *Town* are $\sim$0.9 and $\sim$0.1 respectively. Based on the rules described in Section 5, the rules that will be assigned with positive strengths are (Wildlife, Few, Irreversible $\mapsto$ Medium), which is assigned to 0.9, and (Wildlife, Town, Irreversible $\mapsto$ Medium), which is assigned to 0.1. Therefore, the membership in the fuzzy set *Medium* used by the fuzzy expert system described in Section 4 is 0.9.

The estimation is that it will take 15 years until the sturgeon becomes extinct (if overfishing and pollution continues). Therefore, the membership of 20 in the fuzzy set *Short* is 0.75, and the degree of membership to the fuzzy set *Immediate* is 0.25. Degrees of membership to all other fuzzy sets defined on the antecedent fuzzy variable *Time* are 0.

The probability of the extinction of sturgeon if overfishing and pollution continues is 1.0, since the current knowledge can determine that overfishing and pollution lead to extinction of species, such as the extinction of lake trouts in the lower great lakes. The degree of membership of 1 in the fuzzy set *High* is 1, and 0 to all other fuzzy sets defined on the antecedent fuzzy variable *Probability*.

The evidence in this case is 100%, since the effect of overfishing and pollution has been well studied, and extinction of fish due to both overfishing and pollution has been recorded in the past. The degree of membership of 1 to the fuzzy set *Strong* is 1, and the degree of membership to all other fuzzy sets defined on the antecedent fuzzy variable *Probability* is 0.

Considering the fuzzy rules listed in Section 4, the only rules that will be assigned with a positive strength value are (Medium, Short, High, Strong $\mapsto$ Balanced) and (Medium, Immediate, High, Strong $\mapsto$ BARD). The strengths of the rules are 0.75 and 0.25 respectively. Using the center-of-mass defuzzification, the weight of evidence determined by the fuzzy expert system in this case is $\sim$55%.

Based on the computed weight of evidence, a court using the proposed system should allow any activity in the Muskegon River, given that the person or organization provided evidence of 55% that the activity does not involve a risk to the sturgeon population. Alternatively, evidence of 45% that shows risk should be enough to stop the activity. In practice, the Michigan Department of Natural Resources law enforcement division decided to forbid fishing activity in the Muskegon River (MDNR, 2004), but did not specify the weight of evidence required for stopping other activities that might introduce risk to the sturgeon population.

Since fuzzy expert systems are usually implemented using computer programs, courts using this approach will not have to go through the calculations described above, but simply type in the numbers and get the determined weight of evidence for the specific case.

7 Conclusion

Determining the weight of evidence in environmental cases is a well-known concern in environmental law. Standard weights of evidence used in criminal cases (0.99) or civil cases (0.51) are not available when implementing the precautionary principle. In this paper we proposed a formal method for determining the weight of evidence in environmental cases based on several objective parameters. The calculation is performed by using a fuzzy expert system. The fuzzy logic model should be defined by regulators, with the assistance and cooperation of a team of environmental science and policy experts. Once the expert system is defined, all courts can use the same model, so that the weight of evidence is quantified in an objective and non-arbitrary fashion that has a minimal dependency on the point of view of the specific person or court making the decisions.

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