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# Combing LCIA and Fuzzy Risk Assessment for Environmental Impact Assessment

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***Abstract*—**Environmental impact assessment (EIA) is a procedure tool of environmental management for identifying, predicting, evaluating and mitigating the adverse effects of development proposals. EIA reports usually analyze how the amounts or concentrations of pollutants obey the relevant standards. Actually, many analytical tools can deepen the analysis of environmental impacts in EIA reports, such as life cycle assessment (LCA) and environmental risk assessment (ERA). Life cycle impact assessment (LCIA) is one of steps in LCA to introduce the causal relationships among environmental hazards and damage. Incorporating the LCIA concept into ERA as an integrated tool for EIA can extend the focus of the regulatory compliance of environmental impacts to determine of the significance of environmental impacts. Sometimes, when using integrated tools, it is necessary to consider fuzzy situations due to insufficient information; therefore, ERA should be generalized to fuzzy risk assessment (FRA). Finally, the use of the proposed methodology is demonstrated through the study case of the expansion plan of the world's largest plastics processing factory.

***Keywords*—**Fuzzy risk analysis, life cycle impact assessment, fuzzy logic, environmental impact assessment

## I. Introduction

ENVIRONMENTAL RISK ASSESSMENT (ERA) is a widely used analytical tool in environmental management. The interpretation of ERA starts with the concepts of hazard and risk. An environmental hazard is an object, event or situation with the potential to cause damage to physical surroundings, resources, ecosystems, humans, etc. Meanwhile, an environmental risk refers to the severity and the likelihood of the damage that will actually occur. Five stages were proposed in a wide-ranging ERA [1] as follows (see Fig. 1). Firstly, problem formulation, sometimes also known as hazard identification, typically implies the identification of the causal linkage of hazard-pathway-receptor-damage. Secondly, release assessment determines the severity of a hazard based on the consideration of its magnitude, spatial extent and temporal duration. Thirdly, exposure assessment has two components: the probability of the hazard occurrence and the probability or degree of the receptors being exposed to the hazard. Fourthly, dose-response assessment covers the probability or degree of damage resulting from exposure to standardized hazards (hazards reaching standard values). The last but not the least important step is risk characterization, which evaluates the significance of a risk by considering the likelihood of the hazard being realized and the severity of the hazard simultaneously.

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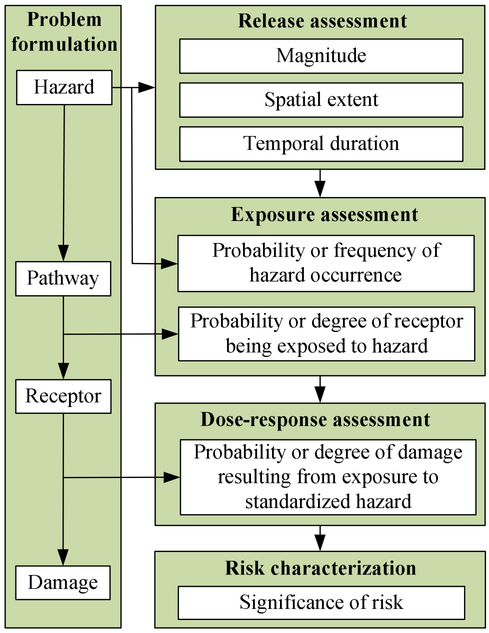


Fig. 1 Framework of environmental risk assessment

Fuzzy risk assessment (FRA) deals with situations where some assessments are performed in light of fuzzy information during these stages of ERA. For example, the assessment of hazard severity can be a subjective decision-making process which is usually modeled by fuzzy logic [2]. Evaluating probabilities of a receptor being exposed to hazard or assessing probabilities of damage resulting from exposure to a standardized hazard can involve precise numbers or probability distributions; whereas, these numbers and distributions may be arrived at through expertise or experience if information is insufficient. Such cases are usually fuzzy and can be converted into possibility distributions. Life cycle assessment (LCA) is another well-known analytical tool in environmental management. LCA carries out environmental impact assessment throughout the entire life cycle of a product, from its origin as a raw material until its end, usually as a waste. One important step in LCA is the life cycle impact assessment (LCIA) which introduces the causal relationships among environmental hazards and damages and devises a methodology for assessing the levels of damages.Thus, incorporating the LCIA concept into ERA (or FRA) can help identify the causal linkage of hazard-pathway-receptor-damage in problem formulation. It can also help us to better understand environmental significance during risk characterization. Indeed, the combination of LCIA and ERA (or FRA) can be a beneficial tool in environmental management. On the other hand, environmental impact assessment (EIA) is a procedure tool which involves the processes of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals before major decisions and commitments made.

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Development proposals for which there is concern of adverse impact on the environment should be subject to EIA reports. These reports should then be transferred to competent authorities for review. EIA reports traditionally elaborate the amounts or concentrations of pollutants and ensure that they obey the relevant standards. Linking LCIA to ERA (or FRA) as a tool for EIA will extend the focus on the regulatory compliance of environmental impacts to assess what kind of and how much damage development projects can cause. This would be helpful for review committees or stakeholders when determining the significance of environmental impacts.

To summarize, this study aims at proposing an integrated framework of LCIA and FRA, considering fuzzy conditions in the framework, and exploiting it as a new analytical tool to help estimate significance in EIA. Finally, the expansion plan of the world's largest plastics processing factory will be used as a study case in order to demonstrate the use of the tool.

## II. Material and Methods

### A. Incorporating the LCIA concept to identify hazard-pathway-receptor-damage

EIA reports traditionally elaborate the amounts or concentrations of pollutants and ensure that they obey the relevant standards. Their focus should be extended from regulatory compliance to interpretation of significance. Environmental significance refers to whether midpoint and endpoint effects caused by pollutants are important for stakeholders. The starting point of evaluating significance is to recognize the possible midpoint effects and damages (endpoint effects) caused by a hazard and determine their importance. Existing LCIA methods provide such a basis for identifying the cause-effect relationship between hazards, pathways, receptors and damages. To develop our version of the cause-effect relationship for identifying hazard-pathway-receptor-damage, a three-step procedure is introduced as follows.

*1. Identification of hazards*

In accordance with the characteristics of the factories we studied, some hazards (pollutants) are selected, as shown in part A of Fig. 2. For example, the IPCC has identified six greenhouse gases causing climate change: carbon dioxide ($CO_2$) coming from fossil fuel combustion, forest clearing, cement production, etc.; methane landfills ($CH_4$) coming from production and distribution of natural gas & petroleum, fermentation from the digestive systems of livestock, rice cultivation, fossil fuel combustion, etc; nitrous oxide ($N_2O$) coming from fossil fuel combustion, fertilizers, nylon production, manure, etc.; hydrofluorocarbons (HFCs) coming from refrigeration gases, aluminum smelting, semiconductor manufacturing, etc.; perfluorocarbons (PFCs) coming from aluminum production, semiconductor industry, etc.; and sulfur hexafluoride ($SF_6$) coming from electrical transmissions and distribution systems, circuit breakers, magnesium production, etc.

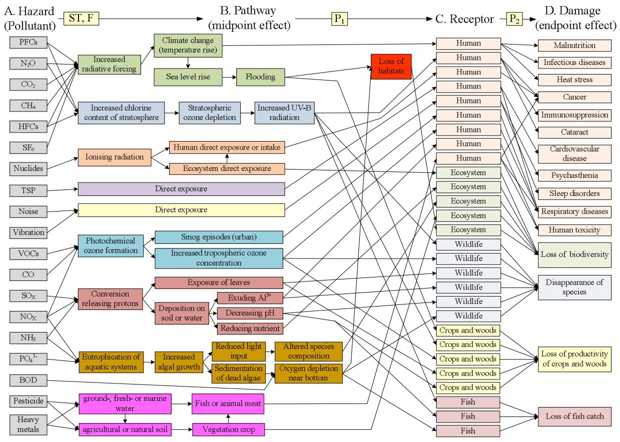

Fig. 2 Overview of the causal relationships between hazards, pathways, effects and possible damages

*2. Identification of pathways*

Prior to determining significance, a diagram of the causal relationships between hazards and receptors that includes all the relevant pathways allows stakeholders to understand the midpoint effects of a pollution emission, as shown in part B of Fig. 2. A hazard may cause several midpoint effects. For example, $N_2O$ can induce climate change and stratospheric ozone depletion simultaneously. On the other hand, $N_2O$, $CO_2$, $CH_4$, PFCs or $SF_6$ can also cause temperature rise and, further, possibly result in the rise of sea level and flooding.

*3. Identification of receptors and their possible damages*

The kinds of damages (endpoint effects) brought about by a midpoint effect depend upon receptors, as shown in parts C and D of Fig. 2. For example, climate change could possibly lead to human malnutrition, infectious diseases, heat stress and the loss of biodiversity in ecosystems resulting in decreased productivity of crops and wood.

### B. Using fuzzy logic for release assessment (S)

Release assessment estimates the severity of a particular hazard (S) which is determined by its magnitude (M), spatial extent (E) and temporal duration (D). The magnitude of a hazard refers to the concentration of its pollution source, usually denoted by ppm, mg/L or mg/m$^3$. The geographical scale of a hazard often extends considerably beyond the boundaries of the source of the hazard. Failure to consider the spatial extent may result in the scope of the risk assessment being too limited [1]. A spatial extent is expressed as the radius of an area where the concentrations are either higher than the standard values, or higher than the double of the average concentrations in neighboring counties if the former condition does not exist. The temporal scale is also an important aspect in release assessment because it may be so prolonged that the damage can be assumed to be permanent and the environment beyond recovery [1]. Temporal factor is measured by the duration of a pollution emission within one year.

Appraising the severity of a hazard can be a subjective decision-making process. This type of appraisal is fulfilled by fuzzy logic [2] in this study. Fuzzy logic can be treated as a tool

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with the ability to compute with words when modeling qualitative human thought processes in the analysis of complex systems and decisions. In fuzzy logic, qualitative perception-based reasoning is represented by "IF-THEN" fuzzy rules. A triangle fuzzy set can be expressed as a 3-truple (l, m, r), where l, m, r are the locations of the left, middle and right peaks of the triangle, respectively.

To evaluate the severities of hazards, 19 rule bases containing 513 fuzzy rules were produced. These 19 rule bases and their corresponding membership functions are constructed based on expertise, and these fuzzy inference systems are implemented with MATLAB Fuzzy Logic Toolbox.

In many cases, the final output of an inference system should be a single number. Defuzzification is a method to justifiably convert a fuzzy set into a precise value. This study utilized the center-of-gravity method, which takes the center of the area under the curve of the membership function of a fuzzy set as the answer. The score of severity for $NO_x$ is 29.5 (S).

*C. Applying severity transformation to compare with standard values (ST)*

Although the scale of outputs of fuzzy logic is from 0.0 to 100.0, the range of real outputs is within this scale. All outputs are linearly transformed so that their lower bounds (5.23) are designated to correspond to 0.0; on the contrary, the outputs of standard values (94.8) correspond to 100.0. For example, the standard value of NOx in the manufacturing processes is 250 ppm; hence, fuzzy logic infers a value of 94.8. The result of severity transformation (ST) is computed by (29.5-5.23)/(94.8-5.23)×100, as 27.1.

*D. Estimating frequency of hazard occurrence (F)*

The frequency of a hazard occurrence is defined as the number of occurrences per year, which can be a precise number, a probability distribution or a possibility distribution. If historical records are sufficient and a precise frequency or a probability distribution over possible frequencies is available; otherwise, the frequencies may be assigned through expertise or experience, which are usually fuzzy and can be converted into possibility distributions [2]. When the methodology is applied to EIA, the frequency is estimated as “1” for a continuous release of pollutants from a factory.

*E. Evaluating probability of receptor being exposed to midpoint effect ($P_1$)*

Further investigation is not required if no actual or potential pathway exists between a hazard and the receptor [1]. For example, heavy metal contamination of soil will not pose a risk to humans if there are no residents near the site. Evaluating the probability of receptor being exposed to a midpoint effect ($P_1$) can be a precise number or a probability distribution if sufficient information is available; otherwise, it can be assigned through expertise or experience, which is usually fuzzy and expressed by a possibility distribution. For example, NOx can increase tropospheric ozone concentration and the probability of the receptors being exposed to the effect is subjectively estimated as “about 0.1,” which is represented as a triangle fuzzy set of 3-truple (0.0, 0.1, 0.2).

*F. Assessing probability of damage resulting from exposure to a standardized hazard ($P_2$)*

The probability of damage (endpoint effect) resulting from exposure to a standardized hazard ($P_2$) is considered as the percentages of humans, ecosystems, crops and woods, wildlife or fish production sustaining damage when pollution reaches standard values. Even exposed to the same midpoint effect, the likelihood of damage is probabilistic and will rely on the likely susceptibility of an individual receptor to the effect. Assessing $P_2$ is an extremely complicated task and is pervaded with uncertainty because the relevant knowledge of toxicology, epidemiology and ecology is still incomplete. Therefore, it will be a precise number or a probability distribution once related knowledge is available; otherwise, it can be assigned subjectively through expertise or experience as a fuzzy number. For example, $NO_x$, $SO_X$, VOCs or CO can increase tropospheric ozone concentration and further cause human respiratory diseases. Their standard values for the outlet of an emission pipe are 250, 650, 100 and 2000 ppm, respectively. The probability of respiratory diseases resulting from exposure to the pollution that has reached standard values is subjectively assessed as “about 0.3,” which is expressed as a triangle fuzzy set of 3-truple (0.2, 0.3, 0.4). The P2 of “about 0.3” denotes that about 30% of human exposure to increased tropospheric ozone concentration caused by the standard values of relevant pollutants will induce respiratory diseases.

*G. Using the vertex method to compute risk of damage (R)*

The vertex method was proposed by Dong and Shah [3] for computing functions of fuzzy variables and is applied herein to compute R in Eq. (1). The vertex method is based on α-cut and the interval analysis technique. Using α-cut, each fuzzy variable characterized by a convex membership function is converted into a group of intervals associated with various α values. Intervals with the same α value from all fuzzy variables are processed by interval analysis, resulting in an interval function with the value. For example, the ST of $NO_x$ is 27.1; F is estimated as “1” for a continuous release of $NO_x$; $P_1$ is subjectively estimated as “about 0.1 (0.0, 0.1, 0.2);” and $P_2$ is “about 0.3 (0.2, 0.3, 0.4),” hence as shown in Fig. 3, the result of R is not exactly but is very similar to a triangle fuzzy number and can be approximately represented as a triangle fuzzy set (0, 0.813, 2.168), which indicates the fuzzy expected value of the percentage of humans getting respiratory diseases through increased tropospheric ozone concentration.

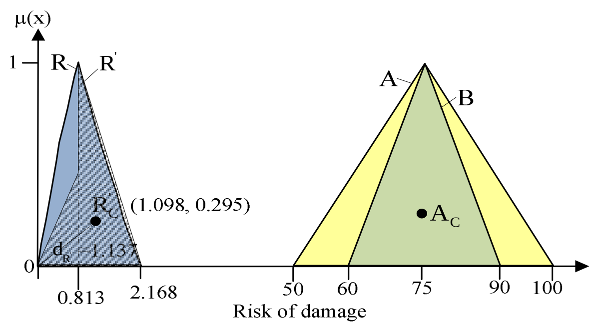


Fig. 3 Result of R through the vertex method

### *H. Employing distance method to defuzzify risk*

Defuzzification is the process of producing a quantifiable result in fuzzy logic, given fuzzy sets and corresponding membership degrees. The last step is to defuzzify risk R in order to obtain a finally precise number. Centroid or distance methods are widely used for defuzzification. Two isosceles triangles, A(50, 75, 100) and B(60, 75, 90), as shown in Fig. 3, should result in different level of risk, but they are not distinguishable by either the centroid method or the distance method because they have the same centroid $A_C$(75.000, 0.333) and, of course, the same distance of 75.001 from the centroid to the origin. In addition, from a conservative point of view, the right wing of the possibility distribution of a risk should be given more emphasis than the left wing. Therefore, the left wing of the possibility distribution of risk R is reduced to half; that is, it is multiplied with a weight of 0.5. The weights for the right and left wings of the possibility distribution of a risk can be determined by a panel of experts. After being scaled down, the left wing of R becomes a new fuzzy number R' with a centroid $R'_C$(1.098, 0.295) and the distance $d_R$' from the centroid to the origin is 1.137, as shown in Fig. 3. The distance $d_R$' indicates the expected value of the percentage of humans getting respiratory diseases through increased tropospheric ozone concentration.

## III. RESULTS AND DISCUSSION

### *A. Case Study*

A plastics factory established in 1958 covers about 178.9 hectares in an industrial zone of Yunlin County, Taiwan. It is the world's largest plastics processing factory, generating plastic products, petrochemical raw materials, electronic materials, polyester fiber products, etc. In 2009, its outputs reached to 3.71 million tons and its turnover was up to 5.4 billion U.S. dollars. In response to the market demand, the company intended to further enhance the supply capacity of raw materials to 5.03 million tons of products and proposed an expansion plan of 28.63 billion U.S. dollars. An associated environmental impact statement (EIS) was submitted for review in December 2009. According to the EIS, the major air pollutants were $SO_X$, $NO_X$, VOCs, CO, TSP and noise and the primary water pollutants in the treated wastewater were BOD and $PO_4^{3-}$. The emission details are listed in Table 2. Before expansion, the emission of $SO_X$, $NO_X$, VOCs, CO and TSP were respectively 838.6 tons, 886.4 tons, 291.2 tons, 3,047.9 ton and 272.5 tons per year, which resulted in concentrations in emission pipes of 54.35 ppm, 48.09 ppm, 46.48 ppm, 432.31 ppm and 29.59 mg/m3, respectively. After expansion, the emissions were predicted to be 942.5 tons, 1,073.2 tons, 416.9 tons, 3,047.9 ton and 341.0 tons, respectively, and the concentrations in emission pipes were 61.09 ppm, 58.23 ppm, 66.53 ppm, 432.31 ppm and 37.02 mg/m3, respectively. Noise was forecasted to increase slightly from 65.95 to 66.15 dB after expansion. The treated wastewater was discharged into the sea at the rate of 187,638 CMD before expansion but was forecasted to reach 257,638 CMD after expansion; and the BOD and $PO_4^{3-}$ were all controlled within the standards (30 and 4 mg/L).

TABLE I
FUZZY RISKS OF DAMAGES AND THEIR DEFUZZIFICATIONS BEFORE AND AFTER EXPANSION

| Pollutant | Damage | Before expansion | After expansion | Increase | |
|---|---|---|---|---|---|
| $SO_X$ | Human toxicity | 1.001 | 1.039 | 0.038 | 3.9% |
| | Loss of biodiversity | 2.554 | 2.658 | 0.104 | |
| | Disappearance of species | 1.001 | 1.039 | 0.038 | |
| | Loss of productivity of crops and woods | 3.140 | 3.269 | 0.128 | |
| | Loss of fish catch | 1.021 | 1.060 | 0.039 | |
| $NO_X$ | Respiratory diseases | 1.137 | 1.255 | 0.118 | 10.8 % |
| | Human toxicity | 1.400 | 1.549 | 0.149 | |
| | Loss of biodiversity | 2.622 | 2.910 | 0.288 | |
| | Disappearance of species | 1.964 | 2.178 | 0.214 | |
| | Loss of productivity of crops and woods | 4.482 | 4.979 | 0.497 | |
| VOCs | Respiratory diseases | 2.163 | 2.787 | 0.624 | **29.1 %** |
| | Disappearance of species | 3.801 | 4.911 | 1.110 | |
| | Loss of productivity of crops and woods | 5.445 | 7.038 | 1.594 | |
| CO | Respiratory diseases | 1.207 | 1.207 | 0.000 | 0.0% |
| | Disappearance of species | 2.090 | 2.090 | 0.000 | |
| | Loss of productivity of crops and woods | 2.983 | 2.983 | 0.000 | |
| TSP | Cardiovascular disease | 2.908 | 3.558 | 0.649 | **22.4 %** |
| | Respiratory diseases | 14.675 | 17.980 | 3.306 | |
| Noise | Psychasthenia | 7.680 | 7.690 | 0.010 | 0.1% |
| | Sleep disorders | 11.173 | 11.188 | 0.015 | |
| BOD | Loss of biodiversity | 9.076 | 9.430 | 0.354 | 3.9% |
| | Disappearance of species | 8.757 | 9.099 | 0.342 | |
| | Loss of fish catch | 24.268 | 25.216 | 0.948 | |
| $PO_4^{3-}$ | Loss of biodiversity | 9.076 | 9.430 | 0.354 | 3.9% |
| | Disappearance of species | 8.757 | 9.099 | 0.342 | |
| | Loss of fish catch | 24.268 | 25.216 | 0.948 | |

### *B. Results*

The damages (endpoint effects) caused by pollutants through various midpoint effects are summarized in the first two columns of TABLE I. In this study, the risk of damage (R) is defined as the multiplication of ST, F, $P_1$ and $P_2$. The vertex method is thereby used to compute R when any of its factors are fuzzy and the output will also be a fuzzy number which is not exactly but is very similar to a triangle and can be approximately represented as a triangle fuzzy set of 3-truple (l, m, r), as shown in Table I. Defuzzification is then applied to R in order to obtain a final precise result. The distance (d) from the centroid (x, y) of R' (with a scaled left wing of R) to the origin is employed as the defuzzification method in this study and is interpreted as the percentage of humans, ecosystems, crops and woods, wildlife or fish production sustaining damage. The fuzzy risks of damages and their defuzzifications are shown in Table I. Before and after expansion, losses of fish resulting from BOD and $PO_4^{3-}$ were severe because of the high STs, as denoted by double-underlines in Table I.

Nevertheless, the risks resulting from VOCs and TSP showed the greatest increases (29.1% and 22.4%) after expansion, as denoted by the bold numbers in Table 4. However, the greatest absolute increase in damage risk were in respiratory diseases caused by TSP, which increased from 14.675 to 17.980, an increase of 3.306; the second absolute increase of 1.594 came in the loss of productivity of crops and woods caused by VOCs; the third absolute increase was 1.110 for the VOCs-caused disappearance of species. The above-mentioned absolute increases are all indicated by single-underlines in TABLE I. It should be noted that although they are the second and third ranking absolute increases, they reach up to 29.1%.

## IV. Conclusions

This study proposed an integrated tool of combining life cycle impact assessment into fuzzy risk assessment through the following steps: incorporating LCIA concept to identify the causal linkage of hazard-pathway-receptor-damage, using fuzzy logic for release assessment, applying severity transformation to compare with standard values, estimating the frequency of hazard occurrence, estimation of the probability of the receptors being exposed to midpoint effects, evaluating probability of receptors being exposed to standardized hazards, using the vertex method to compute risk of damage, and employing distance method to defuzzify risk. The tool can extend the focus on the regulatory compliance of environmental impacts to determining significance in environmental impact assessment.

The integrated tool was demonstrated with a practical case study. The release assessment shows that the STs of BOD and $PO_4^{3-}$ are very high before and after expansion due to their high concentrations. However, the greatest relative increases in ST are VOCs (by 29.3%) and TSP (by 22.6%). The risk characterization shows the high STs in BOD and $PO_4^{3-}$ also lead to severe loss of fish caught of more than 20.0. Meanwhile, the risks resulting from VOCs and TSP have the greatest relative increases (29.1% and 22.4%) after expansion. However, the greatest absolute increase in risks is 3.306 for the respiratory diseases caused by TSP. Furthermore, the joint risk of respiratory diseases exceeds 20.0 and has the greatest absolute increase (3.750) which implies an increase in the expected value of the percentage of humans getting respiratory diseases. Assuming the risk of respiratory diseases resulting from TSP can be cut down from 17.980 to 16.135, which means the concentration of TSP should be reduced from 37.02 mg/m3 to 32.73 mg/m3 and its emission can be reduced from 341.0 ton to 301.4 ton by installing more dust collectors, the increase of 3.750 will be cut down to 2.000.

We encountered several difficulties in integrating the LCIA concept and FRA as a tool for EIA. Further work is still required to overcome these difficulties. The first step is to consider the probabilities of midpoint effects (e.g. Climate change) resulting from environmental hazards (e.g. $CO_2$ emission). This type of probability was neglected in study paper because some of them are still under debate in the scientific community. The second difficulty was in gathering sufficient epidemiological studies to determine the probability of damages resulting from exposure to standardized hazards. Hence, we exploited subjective judgment when assigning the associated probabilities. The third difficulty came from combining the joint risks of damages resulting from various midpoint effects, which compelled us to make an independence assumption when aggregating risks. If these difficulties can be overcome, this model will be very beneficial in EIA.

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