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An approach to estimating the individual risk for toxic-gas releases using the load-resistance model

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ABSTRACT

A new approach to quantify the uncertainty of the individual risk for toxic releases is presented in this paper. The individual risk is defined as the probability of fatality per year. The probability of fatality is calculated by a classical load-resistance model based on reliability (survivability) theory. The load effect is defined as the concentration intensity to which a human is exposed. Furthermore, the resistance is defined as the human tolerance to a certain concentration load in this study. The Monte Carlo method is used to obtain the probability distributions of outputs (the load effect and resistance) propagated from the uncertainties of the input variables. The fatality probability exceeding a limit state can then be obtained by comparing pairs of samples from the load effect and the resistance distributions. The separation of sampling from the load and resistance distributions is also proposed to allow more efficient calculation than that achieved by the classical Monte Carlo method. The analytical risk estimates computed by the load-resistance model are compared to conventional risk estimates that correspond to the upper-end percentile of the load-effect distribution. A case study shows that the conventional risk estimates can be directed to wrong decisions when the load-effect distribution has upper-end tail heaviness.

1. Introduction

1.1. Quantitative risk assessments for land-use planning

Although quantitative risk assessment method has been successfully adopted to improve plant safety and also to perform emergency planning, the quantitative risk assessment in the Netherlands is mainly applied to land-use (spatial) planning in the context of so-called external safety. An elaborate review on the quantitative risk assessment and its relation with land-use planning has recently been published (Pasman & Reniers, 2014). The external safety (off-site safety) policy is based on the risk management approach, which involves quantitative assessment of risks and evaluation against quantitative tolerability criteria (Bottelberghs, 2000).

The methodological approaches for land-use planning can be divided into three broad categories, namely, deterministic, consequence-based, and risk-based approaches (Christou, Gyenes, & Struckl, 2011). The deterministic approaches use pre-defined separation distances. These distances are usually derived from implicit judgment of risk. The consequence-based approach is based on the assessment of consequences of conceivable accidents, without explicitly quantifying the likelihood of these accidents. A typical example of the consequence-based approach is the determination of the worst case scenario expressed as a risk distance. The risk-based approaches for land-use planning define the risk as a combination of the consequences derived from the range of possible accidents, and the likelihood of these accidents.

In Korea, the approaches for land-use planning in the vicinity of hazardous installations fall mostly into the category of the deterministic approaches. Nevertheless, as an exceptional measure, a disastrous explosion of LPG filling station in Korea (Park et al., 2006) led to the development of an evaluation system that is based on quantitative assessment of risks, and then prompted the authority to implement risk-based land-use planning for LPG filling stations in 2002. If any building is located in the vicinity of an LPG filling station, it is evaluated whether the building would come inside the risk contours corresponding to individual risk of 10^{-6} per year. If so, additional safety measures are required that enable compliance with the risk criteria. In 2012, another catastrophic

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release of toxic chemical (hydrofluoric acid) caused widespread damages to crops and livestock in southern Korea. The accident has prompted an extensive discussion on adopting risk-based policies for facilities handling toxic substances (Kim, Lee, & Moon, 2014).

In general, two quantitative risk measures, namely, individual risk and societal risk are used to evaluate risk acceptability for hazardous activities. The individual risk for a point-location around a hazardous activity is defined as the probability that an average unprotected person permanently present at that point location, would get killed due to an accident at the hazardous activity (Bottelberghs, 2000). The societal risk for a hazardous activity is defined as the probability that a group of more than N persons would get killed due to an accident at the hazardous activity (Bottelberghs, 2000). The individual risk is displayed in the form of iso-risk contours on a geographic map. The iso-risk contours give information on the risk of a location. Thus this paper focuses on the individual risk as a quantitative risk measure for land-use planning.

1.2. Uncertainty quantification

In many engineering situations, most variables used in the analysis will be associated with uncertainty. In performing a quantitative risk analysis it is important to identify how these uncertainties affect the result. Basically, uncertainty can be classified into two categories: aleatory uncertainty (or variability), and epistemic uncertainty (or uncertainty) (Helton & Burmaster, 1996). Variability is the inevitable variation inherent in a process which is caused by the randomness in nature. For instance, the natural variability of weather affects the dispersion processes of toxic gases (Scenna & Cruz, 2005). The variability can be better characterized with more data, but it cannot be reduced or eliminated. The epistemic uncertainty, on the other hand, represents a lack of knowledge about fundamental phenomena. This type of uncertainty can be reduced through greater understanding of the system.

Since the 1980s the United States Environmental Protection Agency (US EPA) has been prominent in developing probabilistic approaches, which handle uncertainty in environmental risk assessment. The probabilistic approach uses probability distributions for one or more variables in a risk equation in order to quantitatively characterize variability (aleatory uncertainty) and uncertainty (shortened for "epistemic uncertainty"). The output of a probabilistic approach is a probability distribution of risks that reflects the combination of the input probability distributions. A quantitative risk assessment performed using probabilistic methods is very similar in concept and approach to the point estimate method, which uses the deterministic values for input variables (USEPA, 2014a).

Monte Carlo method has been widely used to propagate variability and uncertainty in probabilistic approaches. The practical application of the method has been facilitated by the development of statistical sampling techniques to obtain a probabilistic approximation to the solution of a mathematical equation. A framework for processing random variables by the Monte Carlo method has also been introduced in a risk-based approach to land-use planning, and it has been applied to obtaining the individual risk as a function of the distance from the hazard sources (Hauptmanns, 2005). If paired data are available for as set of model input variables, the paired data can be used directly employing a technique known as bootstrap sampling method that generates a set of Mote Carlo sample by re-sampling directly from the original data sets.

In this work, site-specific meteorological data sets are used to consider the stochastic variability. The bootstrap sampling method is adopted here to avoid the regression errors of parametric estimates, and to reduce the effect of neglecting the correlation among the meteorological variables.

1.3. Direction-dependent hazard

If toxic gas is released from a source, it will drift downwind. A receptor positioned downwind from the release source is more risky than one positioned upwind. In other words, the vulnerability of the receptor strongly depends on the meteorological conditions (Sullivan, Holdsworth, & Hlinka, 2004). For this reason, the prevailing wind direction should be considered in land-use planning or chemical-plant siting, if meteorological data are available (CCPS, 2003; Mannan, 2005).

For considering the wind direction in quantitative risk assessments, Center for Chemical Process Safety (CCPS) guidelines (CCPS, 1999, 2000) have adopted eight discrete wind directions to account for the variability in the wind direction. A case study in the guidelines showed that a relative probability of the occurrence of wind in each wind sector was simply applied to dispersion modeling, even though the wind sector does not correspond with the arc of the plume. The Netherlands Organization of Applied Scientific Research (TNO) (Haag & Ale, 2005) suggested an individual risk calculation method using the concept of the effective cloud width instead of the plume arc, which does not correspond with the arc of the wind sector, whereas the effective cloud width represents a cross-wind width of the cloud corresponding to 1% of fatality. The TNO model assumed that a plume could affect the receptors in the adjacent wind sectors when the width of the plume is larger than the width of the wind sector.

Probabilistic approaches considering directional or geographical effects by the stochastic variability of the wind direction have recently been demonstrated to calculate the spatial risk from toxic gas-dispersion scenarios in road-risk analysis (Godoy, Cruz, & Scenna, 2007; Scenna & Cruz, 2005) and, similarly, to solve layout-optimization problems for a chemical plant from which a toxic gas could be released (Jung, Ng, Lee, Vazquez-Roman, & Mannan, 2010; Vázquez-Romána, Lee, Jung, & Mannan, 2010).

The effect of the wind direction that is caused by the randomness in nature must be inevitable variation in a toxic gas-dispersion process. On the other hand, article 12 of the Seveso II Directive requires land-use policies must consider the need of economy for long term sound and predictable conditions (Christou, Struckl, & Biermann, 1999). Therefore, the stochastic variation of wind direction for the long term is not necessarily the basis for emergency planning, but may rather be considered as a matter of long term strategic planning of the use of land.

1.4. Estimates of risk

Monte Carlo techniques are a common tool in all stochastic applications. Thus, the meteorological variables have been treated as Monte Carlo variables to fully account for the input conditions in the dispersion model or the diffusion model (Burmaster & Anderson, 1994; Hanna, Chang, & Fernau, 1998; Sassi, Vernai, & Ruggeri, 2007; Schaubergera, Piringer, & Baumann-Stanzer, 2013; Sullivan et al., 2004; Yegnan, Williamson, & Graettinger, 2002). The authors have focused on estimating the pollutant concentration distribution at a desired endpoint. A representative exposure, which is generally described by the concentration, corresponding to the 5th, 50th, and 95th percentiles from the outputs of the Monte Carlo simulation at a receptor point, can be selected to determine the output distribution. In general, the risk-estimate protocols tend to produce point estimates that exceed the 95th percentile of the Monte Carlo probability distribution. US EPA has advised that the reasonable maximum exposure at the upper end of the range of risk estimates, generally between the 90th and 99.9th percentiles, called the reasonable maximum exposure (RME) range, should be selected in a probabilistic risk assessment (USEPA, 2014a). ECHA's