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MODELLING UNCERTAINTIES IN ASSESSING RISKS TO STRUCTURES CAUSED BY ACCIDENTAL EXPLOSIONS

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1. Introduction

Accidental explosions commonly referred by the abbreviation UVCE (unconfined vapour cloud explosions) constitute real dangers to many industrial facilities involved into storage, transportation, processing and use of such inflammable and explosive materials as liquefied petroleum gas (LPG). The risks arising from release, vaporisation and ignition of these materials involve usually damages to structural systems built both inside and outside the dangerous facility under consideration. Major accidents involving UVCE(s) as, for instance, the disaster in the PEMEX LPG-facility [1, 2], are characterised by considerable degree and area of damages to structural systems.

An estimation of magnitude (character) and annual probability of the potential damages to structural systems, which may be caused by the accidental explosions, is an important problem of assessing the existing structural systems adjacent to a dangerous facility and valuation of the facility itself. A natural way to solve this problem is an application of the quantitative risk assessment (QRA) methods in combination with those of the structural reliability analysis (SRA).

In attempting to estimate risks to structures coming from the explosions, the major focus of attention should be directed to the interface between QRA and SRA, namely, hazard functions of mechanical effects of the accidental explosions. From the standpoint of structural analysis, three mechanical effects – peak initial overpressure, impulse and duration of reflected blast wave generated by an incident blast wave of accidental explosion – are most important [3].

Hazard functions characterise random mechanical effects of accidental explosions in terms of annual exceedance probability versus intensity. Establishing the

hazard functions for a particular structural system being exposed to dangers of a particular nearby facility is a problem facing serious difficulties.

Hazard functions are probabilistic models chosen on the basis of statistical data or, in other words, fitted to statistical data. The amount of data in the situation of particular exposure of structural system will in most cases be insufficient; data on accidents related to the particular exposure may be unavailable at all. Moreover, generic data on the accidents of the type of interest collected nation-wide or even world-wide may be inappropriate for the situation of the particular exposure, especially as regards the estimation of annual probabilities of exceedance.

On the other hand, there exists a detailed knowledge related to the accidents considered and having the form of numerical and analytical information, which allows an approximate numerical modelling of physical phenomena preceding the accidental explosions and assessing mechanical effects of them. This knowledge involves

- (1) general methods of QRA and reliability analysis allowing to estimate the annual probability of release of LPG as well as characteristics of that release;
- (2) methods used to model dispersal of released LPG (eg [4, 5]);
- (3) information on primers (ignition sources) which may initiate deflagration and detonation of vapour clouds formed in consequence of an accidental release of LPG (eg [6]);
- (4) models describing atmospheric conditions at the site where an accident leading to an explosion can occur, such as models used to forecast wind direction and speed;
- (5) models allowing to assess the mechanical effects of explosions (detonations and deflagrations) of the vapour clouds (eg [7–12]);

(6) some amount of statistical data allowing to choose particular models and to estimate their parameters and, first of all, data on accidents in LPG facilities (eg [13, 14]).

With this information, data for statistical fitting of a hazard function may be generated by a numerical modelling of accident courses. Clearly, such a modelling should take into account all uncertainties related to the accident courses and propagate them to uncertainties in parameters of the hazard function.

It is reasonable to suppose that the complexity of the UVCE phenomenon as well as the sum total of phenomena leading to an UVCE predetermines the necessity to deal with all types of uncertainty known in QRA. Although it is advocated that a distinction between different types of uncertainty has not a solid basis at the fundamental theoretical level, a distinction between allegory and epistemic uncertainty is considered as useful for practical QRAs [15, 16]. Consequently, the form of hazard functions should express quantitatively both types of uncertainty. The means to do it have been developed in the methodologies of QRA known as the classical and fully Bayesian approaches to risk quantitation [17–19].

The present paper proposes a procedure of stochastic simulation intended to generate data in the form of statistical samples, which allow to fit hazard functions characterising the mechanical effects of UVCE-type explosions and to express quantitatively uncertainties in their parameters. The proposed procedure by its very nature serves to progress uncertainties related to physical and statistical models of the explosion and all phenomena preceding the explosion to uncertainties expressed by the hazard functions. The procedure relies on the classical Bayesian approach to QRA and is focused on random characteristics of incident blast waves (shock fronts) generated by the explosions. In principle, it can be extended to describe characteristics of reflected blast waves, that is, dynamic actions on structural systems being exposed to the danger of UVCE.

2. Main ideas and scope of the proposed procedure

The subsequent consideration is based on the assumption that characteristics of accidental release of

LPG (amount of released gas, speed of release, etc.) as well as the characteristics of pressure signal of the shock front generated by an explosion of a vapour cloud formed in consequence of that release may be modelled by respective hazard functions, each having the form of a complementary joint cumulative distribution function (c.d.f.), namely,

$$H_Y(\mathbf{y} | \boldsymbol{\pi}_y, p_r) = p_r (1 - F_Y(\mathbf{y} | \boldsymbol{\pi}_y))$$

$$(p_r > 0; y_i \geq 0, i = 1, 2, \dots, n_y)$$

and

$$H_X(\mathbf{x} | \boldsymbol{\pi}_x, p_d) = p_d (1 - F_X(\mathbf{x} | \boldsymbol{\pi}_x))$$

$$(p_d > 0; x_i \geq 0, i = 1, 2, \dots, n_x) \quad (1)$$

where p_r is the annual probability of release of LPG; $F_Y(\mathbf{y} | \boldsymbol{\pi}_y)$ is a joint c.d.f. with vector of components $\boldsymbol{\pi}_y$ describing characteristics of release modelled by the random vector \mathbf{Y} ; n_y is the dimension of the vector \mathbf{Y} ; p_d is the annual probability of explosion of the vapour cloud; $F_X(\mathbf{x} | \boldsymbol{\pi}_x)$ is a joint c.d.f. describing characteristics of the pressure signal of the shock front generated by a detonation of the vapour cloud. In the notations p_r and p_d , the subscripts “r” and “d” stand for “accidental release” and “detonation”, respectively.

The complementary c.d.f.s $H_Y(\mathbf{y} | \boldsymbol{\pi}_y, p_r)$ and $H_X(\mathbf{x} | \boldsymbol{\pi}_x, p_d)$ are composed of frequencies (annual probabilities) p_r and p_d having the dimension of an inverse time period, say, year⁻¹ and dimensionless conditional exceedance probabilities

$$P \left(\bigcup_{i=1}^{n_y} (Y_i > y_i) \middle| E_0 \right) = (1 - F_Y(\mathbf{y} | \boldsymbol{\pi}_y))$$

and

$$P \left(\bigcup_{i=1}^{n_x} (X_i > x_i) \middle| E_3 \right) = (1 - F_X(\mathbf{x} | \boldsymbol{\pi}_x))$$

where E_0 and E_3 denotes the events of accidental release of LPG and detonation of vapour cloud, respectively (see the event tree diagram given in Fig 1). The functions $H_Y(\mathbf{y} | \boldsymbol{\pi}_y, p_r)$ and $H_X(\mathbf{x} | \boldsymbol{\pi}_x, p_d)$ are of the general type and do not restrict the analyst in the choice of their particular form. The function $H_Y(\mathbf{y} | \boldsymbol{\pi}_y, p_r)$ and distributions expressing epistemic uncertainties in its parameters are considered here as inputs into the procedure applied to choose the function $H_X(\mathbf{x} | \boldsymbol{\pi}_x, p_d)$. They are assumed to be known in advance.

The function $H_X(\mathbf{x}|\boldsymbol{\pi}_x, p_d)$ models the stochastic (aleatory) uncertainty in values of the vector X . Another kind of uncertainty accompanying the choice and application of the hazard function $H_X(\mathbf{x}|\boldsymbol{\pi}_x, p_d)$ is related to its parameters given by the scalar p_d and the vector, $\boldsymbol{\pi}_x$, or even to the form of the function $H_X(\mathbf{x}|\boldsymbol{\pi}_x, p_d)$, that is to the distribution type. The latter uncertainty is called the epistemic uncertainty [16–18]. The problem considered below is how to choose the particular form of the hazard function $H_X(\mathbf{x}|\boldsymbol{\pi}_x, p_d)$ and how to express quantitatively the epistemic uncertainty in its parameters. A procedure based on the Monte Carlo simulation is proposed to tackle this problem.

The possible courses of an accident triggered by an accidental release of LPG are represented by the event tree diagram shown in Fig 1. In terms of the quantitative analysis of this event tree, the annual probability of explosion of accidentally released LPG, p_d , can be expressed as

$$\begin{aligned} p_d &= P(E_0 \cap E_1 \cap E_2 \cap E_3) \\ &= P(E_1 \cap E_2 \cap E_3 | E_0) P(E_0) \\ &= P(E_1 \cap E_2 \cap E_3 | E_0) p_r \end{aligned} \quad (2)$$

where E_0 , E_1 , E_2 and E_3 are the random events of initial accidental release of LPG, release such amount of LPG that can generate an explosion, ignition of the vapour cloud formed in consequence of the release and explosion of the vapour cloud, respectively. The event E_0 is taken as an initiating event of the event tree diagram modelling event sequences, which may follow the release, and comprising the sequence $E_0 \cap E_1 \cap E_2 \cap E_3$ (Fig 1).

The traditional quantitative event tree analysis (ETA), by definition, can only yield an estimate of the annual explosion probability p_d , which is expressed in ETA through estimates of the branching probabilities

$$p_i = P\left(E_i \mid \bigcap_{j=0}^{i-1} E_j\right) \quad (i = 1, 2, 3).$$

This analysis can not produce statistical information allowing to fit a particular form of the c.d.f. $1 - F_X(\mathbf{x}|\boldsymbol{\pi}_x)$. However, a collection of such information may be realised through a numerical modelling of courses of the accident, which logical model is the event tree given in Fig 1.

The modelling may be accomplished by applying the Monte Carlo simulation and replace, in some sense, physical experimentation with or observation of full-scale accidents. Such a numerical modelling, subsequently referred to as “modelling accident courses”, has already been applied in some fields of QRA, as for instance, in an assessment of damages to structures and facilities due to wind-borne missile impact loads or in simulation of spread of tank fires in chemical plants [20, 21, 23]. In the present paper, it is proposed to utilise the modelling of accident courses to a choice of the hazard function given by Eq (1).

The modelling of accident courses depicted by the event tree shown in Fig 1 is based on two parallel computations. The first one yields relative frequencies allowing to estimate the probability $P(E_1 \cap E_2 \cap E_3 | E_0)$, and the second one is used to get random realisations of the characteristics of pressure signal,

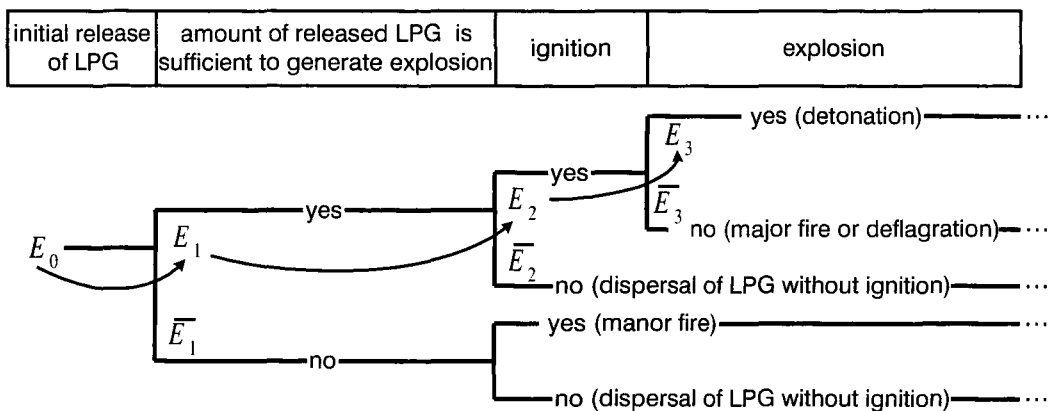


Fig 1. A part of the event tree for the accident in the LPG facility initiated by a release of LPG

$X_i (i = 1, 2, \dots, n_x)$. Both computations complement each other and allow not only to choose the particular form of the hazard function $H_X(x|\pi_x, p_d)$, but to express quantitatively uncertainties in the parameters of this function as well.

3. Modelling accident courses

The modelling of accident courses consists in a numerical simulation of characteristics of physical phenomena related to the events from the tree diagram shown in Fig 1. The modelling is carried out by applying the Monte Carlo simulation. It is repeated many times. One of the possible event tree paths is obtained each time, that is, one of the sequences of physical phenomena constituting the path occurs.

Values of the physical phenomena characteristics are computed by applying their mathematical models. In a concise form, the mathematical models may be expressed as

$$I_k(z_k, \pi_k) = \begin{cases} 1 & \text{if } \mathbf{m}_k(z_k, \pi_k) \in \Delta_k \\ 0 & \text{if } \mathbf{m}_k(z_k, \pi_k) \notin \Delta_k \end{cases}; k = 1, 2, \dots, n_k \quad (3)$$

where z_k and π_k are the vector of inputs into the k th model and the vector of parameters of this model, respectively; $\mathbf{m}_k(\cdot)$ is the vector function of outputs of the k th model; Δ_k is the domain of outputs meaning an occurrence of the k th physical phenomenon if $\mathbf{m}_k(z_k, \pi_k)$ belongs to Δ_k componentwise and a non-occurrence otherwise; n_k is the number of models applied in the simulation of physical phenomena. In the k th model $\mathbf{m}_k(z_k, \pi_k)$, components of the vector z_k are relevant outputs of the preceding models $\mathbf{m}_{k-1}(z_{k-1}, \pi_{k-1})$, $\mathbf{m}_{k-2}(z_{k-2}, \pi_{k-2})$, \dots .

As a simple illustration of the definition (3), one can take the model $\mathbf{m}_1(z_1, \pi_1)$, which should be used to decide whether a vapour cloud in explosive condition may be formed from released LPG (whether the event E_1 occurs). The inputs into the model (components of the vector z_1) are the mean speed of release of LPG, z_{11} (kg/s), and the duration of the release until it is stopped or stops by itself, z_{12} (s). At the same time, the two inputs are components of the vector y , that is, $z_{11} = y_1$ and $z_{12} = y_2$. The model has the form

$$I_1(z_1|\pi_1) = \begin{cases} 1 & \text{if } z_{11} z_{12} - \pi_1 > 0 \\ 0 & \text{otherwise} \end{cases}$$

where π_1 is the threshold of amount of released LPG (kg). The model relies on the fact that there exists a minimal value of the released amount of LPG below which no escalation leading to a detonation of vapour cloud can occur [24]. In this simple case, the vector of parameters, π_1 , has only one component, and the model has only one output given by the expression $z_{11} z_{12} - \pi_1$.

More complicated models than the one just described have been suggested in the literature and are used in modelling accident courses to produce time-histories of spreading gas cloud and changes of its concentration as well as the presence, position and energy of potential primers (ignition sources) ([4, 5] for the models).

In principle, a more general definition of models $\mathbf{m}_k(z_k, \pi_k)$, say, the one based on the Apostolakis-Laskey scheme [19, 22] may be applied. However, the present paper considers the simplified case that no competitive models are applied to a modelling of any of the physical phenomena leading to an explosion.

The number of repetitions of accident courses (number Monte Carlo loops) during one simulation run from here on is denoted by n_r , where the subscript r , as in the case of the annual probability p_r , stands for "accidental release". In the current repetition, the simulation consists in a subsequent deciding, which of the possible alternatives represented by the branching point reached at the moment has occurred (see the event tree shown in Fig 1). The simulation is focused on the event tree path represented by the event sequence $E_0 \cap \dots \cap E_3$. The current loop is terminated and the next one started anew, as soon as the first of the opposite events \bar{E}_i ($i = 1, 2, 3$; $P(E_i) + P(\bar{E}_i) = 1$) occurs (Fig 1).

Each repetition of accident course modelling the event sequence $E_0 \cap \dots \cap E_3$ differs from others in statistical sense or, more precisely, in values of characteristics of physical phenomena, from the accidental release of LPG to the explosion of the vapour cloud formed as a result of this release. To designate this, outputs of the k th model computed in the j th simulation loop are denoted by $\mathbf{m}_k(z_{kj}, \pi_{kj})$ ($k = 1, 2, \dots, n_k$; $j = 1, 2, \dots, n_r$). Here z_{kj} is the value of the vector z_k , which components are relevant outputs of preceding models computed in the j th simulation loop, and π_{kj}

denotes values of parameters of the k th model applied in the current simulation run, in this instance, the l th simulation run. Vector p_{kl} is sampled from a probability distribution expressing epistemic uncertainty in parameters of the k th model and represented by a c.d.f. $F_{\Pi_k}(\pi_k | \pi_{\Pi_k})$ with the vector of parameters π_{Π_k} (see Sec 4 for details).

The aim of the accident courses modelling is to estimate the annual probability of explosion, p_d , and to simulate a sample of characteristics of its pressure signal, x_i ($i = 1, 2, \dots, n_d$), where the sample size, n_d , equals to the number of explosions (occurrences of the event sequence $E_0 \cap \dots \cap E_3$) counted during one simulation run consisting of n_r repetitions of accident courses ($n_d \leq n_r$). An estimate of the annual probability of explosion, p_d , follows from the formula (2), in which the conditional probability $P(E_1 \cap E_2 \cap E_3 | E_0)$ is replaced by corresponding relative frequency n_d/n_r . The sample x_i ($i = 1, 2, \dots, n_d$) may be further used to choose the form of the c.d.f. $F_X(x | \pi_x)$ and to estimate its parameters (see definition of the hazard function by Eq. (1)).

4. Modelling uncertainties

The hazard function $H_X(x | \pi_x, p_d)$ defined by Eq (1) expresses the stochastic uncertainty related to the entire range of magnitudes of random characteristics of pressure signal, X_r . Another kind of uncertainty is related to the hazard function itself or, more specifically, to its constituents p_d and $F_X(x | \pi_x)$. There exists an epistemic uncertainty in values of the annual probability of explosion, p_d , and components of the vector of parameters, π_x . In principle, there can exist an uncertainty in the particular form of the c.d.f. $F_X(\cdot)$. The latter uncertainty, however, is not considered in the present paper.

According to the Bayesian (subjectivistic) approach to QRA, the uncertainty in values of p_d and π_x can be expressed by means the random variable P_d and the random vector Π_x characterised by a simple c.d.f. $F_{P_d}(p_d | \pi_{P_d})$ and a joint c.d.f. $F_{\Pi_x}(\pi_x | \pi_{\Pi_x})$ with the vectors of parameters π_{P_d} and π_{Π_x} , respectively (see general considerations on the Bayesian approach to PRA in [16–18]). These c.d.f.s play the role of prior or posterior distributions.

The particular feature of the problem considered in the present paper is that a usual upgrading of the

functions $F_{P_d}(\cdot)$ and $F_{\Pi_x}(\cdot)$ by standard means of the Bayesian analysis is hardly possible because of the virtual lack of data, which could enable such an upgrading. Accidental explosions of the type considered are rare events and, if they occur, pressure signals are generally not measured. Moreover, the experimental data on non-accidental explosions of vapour clouds seem to be too scarce to perform the upgrading of the functions $F_{P_d}(\cdot)$ and $F_{\Pi_x}(\cdot)$ (see information on experimentation with gaseous explosions and experimental data in [8–10]).

The main idea of the present paper is to relate the c.d.f.s $F_{P_d}(p_d | \pi_{P_d})$ and $F_{\Pi_x}(\pi_x | \pi_{\Pi_x})$ expressing the epistemic uncertainty in values of p_d and π_x with the c.d.f.s $F_{P_r}(p_r | \pi_{P_r})$ and $F_{\Pi_y}(\pi_y | \pi_{\Pi_y})$ modelling epistemic uncertainties in constituents of the hazard function $H_Y(y | \pi_y, p_r)$, that is, in the parameters p_r and π_y , as well as with the c.d.f.s $F_{\Pi_k}(\pi_k | \pi_{\Pi_k})$ ($k = 1, 2, \dots, n_k$), which model epistemic uncertainties in parameters of the mathematical models of physical phenomena leading to an explosion (see Eq (3)). In the c.d.f.s $F_{P_r}(\cdot)$, $F_{\Pi_y}(\cdot)$ and $F_{\Pi_k}(\cdot)$, the subscripts P_r , Π_y , and Π_k denote random variable and two random vectors used to model uncertainties into values p_r , π_y , and π_k , respectively. Given a relation between the two aforementioned groups of uncertainty distributions, the Bayesian upgrading of $F_{P_d}(\cdot)$ and $F_{\Pi_x}(\cdot)$ may be realised through upgrading of the “lower-level” distribution functions $F_{P_r}(\cdot)$, $F_{\Pi_y}(\cdot)$ and $F_{\Pi_k}(\cdot)$.

The epistemic uncertainties in values of p_r , π_y and π_k may be considered as lower-level uncertainties in relation to the ones in p_d and π_x . One might expect that the amount of accidental and experimental data on the release of LPG modelled by $H_Y(y | \pi_y, p_r)$ as well as on physical phenomena modelled by $m_k(z_k, \pi_k)$ is considerably larger than that of accidental explosions of vapour clouds related to the situation of particular exposure of the structural system being analysed. In this case, the choice of the c.d.f.s $F_{P_r}(\cdot)$, $F_{\Pi_y}(\cdot)$ and $F_{\Pi_k}(\cdot)$ as priors and their upgrading is a simpler problem with reference to that of the choice and upgrading of the c.d.f.s $F_{P_d}(\cdot)$ and $F_{\Pi_x}(\cdot)$.

The relation between the groups of c.d.f.s $F_{P_d}(\cdot)$ and $F_{\Pi_x}(\cdot)$, on the one hand, and $F_{P_r}(\cdot)$, $F_{\Pi_y}(\cdot)$ and $F_{\Pi_k}(\cdot)$, on the other, may be established by applying the modelling of accident courses described in Sec 3.

5. Computational scheme

A “loop in loop” scheme may be applied to choose the c.d.f.s $F_{p_d}(p_d|\pi_{p_d})$ and $F_{\pi_x}(\pi_x|\pi_{\pi_x})$. The scheme consists of two simulation loops used to execute the modelling of accident courses (Fig 2).

The outer loop (loop A) is used to sample random values from the distribution of the release probability, $F_{p_r}(p_r|\pi_{p_r})$, and the distributions of parameters, $F_{\pi_k}(\pi_k|\pi_{\pi_k})$. The index of the outer loop, l , takes the values from 1 to n_p . The result of each execution of the outer loop is a sampled value of the release probability, p_{rl} , and sampled vectors of parameters, π_{kl} . With the values p_{rl} and π_{kl} as inputs for the inner loop (loop B), this loop is executed n_r times.

The computation inside the loop B consists of (a) sampling of the value y_j from the distribution $F_Y(y|\pi_{y_l})$, (b) computing outputs of the models applied, $m_k(z_{kj}, \pi_{kl})$ ($k = 1, 2, \dots, n_k$), (c) deciding on the basis of these outputs, whether the event sequence $E_0 \cap \dots \cap E_3$ have occurred in the current repetition of the loop, and, if the sequence has occurred, (c) computing a realisation of characteristics of the pressure signal, x_{jl} . Considered as the l th simulation run, the loop B yields (i) a sample of characteristics of pressure signal, x_{il} ($i = 1, 2, \dots, n_{dl}$), where n_{dl} is the number of explosions countered in the l th simulation run, and (ii) an estimate of the probability of explosion given by

$$p_{de,l} = \frac{n_{dl}}{n_r} p_{rl}$$

An execution of both loops A and B requires modelling accident courses $n_p \times n_r$ times. The result of this modelling is a sample of estimates of explosion probability, $p_{de,l}$ ($l = 1, 2, \dots, n_p$), and a set of samples of the vector of parameters of pressure signal, x_{il} ($i = 1, 2, \dots, n_{dl}; l = 1, 2, \dots, n_p$).

The values $p_{de,l}$ may be used to fit a c.d.f. $F_{p_d}(p_d|\pi_{p_d})$, which will express the uncertainty in probability of explosion. Each sample x_{il} ($i = 1, 2, \dots, n_{dl}$) may serve to fit a particular form of the c.d.f. $F_X(x|\pi_x)$. In the specific case that the same form of $F_X(x|\pi_x)$ is suitable for each of the n_p samples, such fitting repeated n_p times will yield a sample of the vector of parameters, π_{xl} ($l = 1, 2, \dots, n_p$). The latter sample, in turn, may be used to fit the c.d.f. $F_{\pi_x}(\pi_x|\pi_{\pi_x})$. This function will express the epistemic uncertainty in values of components of the vector of parameters, π_x . In a more general case, a family of the c.d.f.s $F_{X_i}(x|\pi_{x_i})$ ($i = 1, 2, \dots, n$) with respective weights (probabilities of subjective confidence in these c.d.f.s) p_i may be chosen on the basis of the samples x_{il} ($i = 1, 2, \dots, n_{dl}; l = 1, 2, \dots, n_p$). A representation of hazard functions in the form of a family of c.d.f.s is usual in some areas of QRA, for instance, in the seismic risk assessment [25].

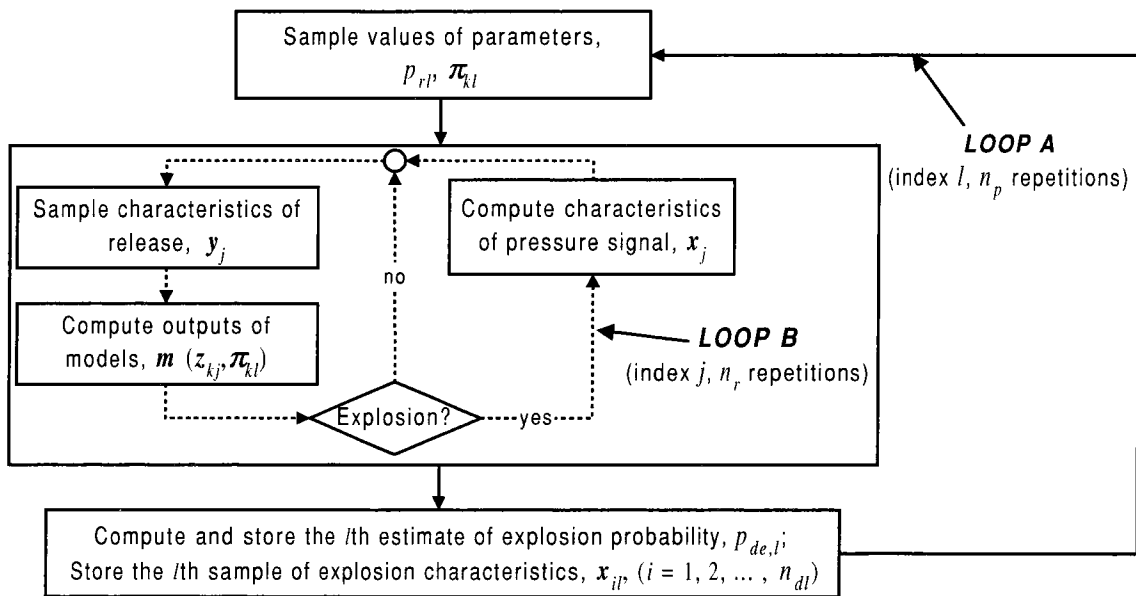


Fig 2. A “loop-in-loop” scheme used in modelling accident courses

An idea how to choose such a family of probability distributions, that is, $F_{X_i}(x|\pi_{x_i})$ ($i = 1, 2, \dots, n$) is described in the next section.

6. Choice of hazard functions

As a preliminary, the choice of the family of c.d.f.s $F_{X_i}(x|\pi_{x_i})$ ($i = 1, 2, \dots, n$) is explained only for the one-dimensional case, that is, only for a component of the vector X , say, for the component X_1 . In this case, the family of c.d.f.s $F_{X_{1l}}(x_1|\pi_{x_{1l}})$ ($i = 1, 2, \dots, n$) may be chosen on the basis of n_r samples x_{1il} ($i = 1, 2, \dots, n_{dl}; l = 1, 2, \dots, n_p$). The choice may be accomplished by applying a five-step procedure described below.

In the first step, values of the variable X_1 are divided into n_1 categories $x_{11}, x_{12}, \dots, x_{1n_1}$ (intervals $[x_{11}, \infty[, [x_{12}, \infty[, \dots, [x_{1n_1}, \infty[$). The categorisation should be accomplished as is done in the classical statistics when establishing cumulative frequency distributions (ogives).

In the second step, cumulative relative frequencies (c.r.f.s) of exceeding the categories $x_{11}, x_{12}, \dots, x_{1n_1}$ are counted for each of these values and each of the samples x_{1il} ($i = 1, 2, \dots; l = 1, 2, \dots$). The result of this counting are n_r samples of c.r.f.s fr_{cl} ($c = 1, 2, \dots, n_1; l = 1, 2, \dots, n_p$), where fr_{il} denotes the c.r.f. of exceedance of the value x_{1i} counted for the l th sample of positive overpressures x_{1il} ($i = 1, 2, \dots, n_{dl}$).

In the third step, a set of an *odd* number of percentiles

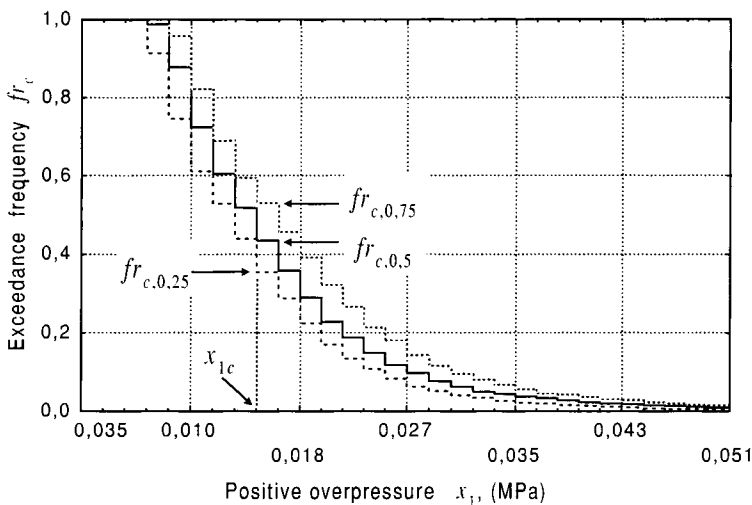


Fig 3. Histograms used to fit the c.d.f.s $1 - F_{X_{1l}}(x_1|\pi_{x_{1l}})$

$$fr_{c,q_1}, fr_{c,q_2}, \dots, fr_{c,q_n}$$

with the pre-set levels

$$q_1 < q_2 < \dots < q_n$$

is found for each sample of c.r.f.s, fr_{cl} ($l = 1, 2, \dots, n_p$). The levels q_1, q_2, \dots, q_n must satisfy the following two conditions:

$$q_{(n+1)/2} = 0,5 \text{ (the percentile } fr_{c,q_{(n+1)/2}} \text{ is the mode)}$$

and

$$\frac{|q_{(n+1)/2} - q_i|}{|(n+1)/2 - i|} \text{ is the same for all } i \neq (n+1)/2.$$

The latter condition means that the levels q_i ($i \neq (n+1)/2$) are “symmetric” about the level $q_{(n+1)/2}$. For instance, the 25th, 50th and 75th percentiles may be found for each sample of c.r.f.s, fr_{cl} ($l = 1, 2, \dots, n_p$). The result of this computation of percentiles are samples of percentiles related to each of the n_1 categories and having the same level, say, the three samples $fr_{c,0,25}, fr_{c,0,5}, fr_{c,0,75}$ ($c = 1, 2, \dots, n_1$).

In the fourth step, the c.d.f.s $1 - F_{X_{1l}}(x_1|\pi_{x_{1l}})$ ($i = 1, 2, \dots, n$) are fitted to corresponding samples of percentiles, namely, to the samples

$$fr_{c,q_1} \quad (c = 1, 2, \dots, n_1),$$

$$fr_{c,q_2} \quad (c = 1, 2, \dots, n_1),$$

...

$$fr_{c,q_n} \quad (c = 1, 2, \dots, n_1).$$

In so doing the number of the c.d.f.s, n results from the number of percentiles found for each category. For instance, three c.d.f.s may be fitted to the three samples $fr_{c,0,25}$ ($c = 1, 2, \dots$), $fr_{c,0,5}$ ($c = 1, 2, \dots$) and $fr_{c,0,75}$ ($c = 1, 2, \dots$).

Finally, in the fifth step, weights p_i are assigned to the fitted c.d.f.s $1 - F_{X_{1l}}(x_1|\pi_{x_{1l}})$ ($i = 1, 2, \dots, n$) depending on the percentiles levels. The following heuristic rule of the assignment may be applied:

$$p_i = \begin{cases} q_i & \text{if } q_i \leq 0,5 \\ 1 - q_i & \text{if } q_i > 0,5 \end{cases} \quad (4)$$

In the case of the three levels 25%, 50% and 75%, the weights assigned are $p_1 = 0,25$, $p_2 = 0,5$ and $p_3 = 0,25$.

The approach expressed by the five-step procedure just outlined is illustrated in Fig 3. The five-step procedure can be easily extended to the multidimensional case, and a family of joint c.d.f.s $1 - F_{X_i}(x|\pi_{x_i})$ ($i = 1, 2, \dots$) fitted in the same manner as in the one-dimensional case.

7. Example

The example illustrates the choice of the hazard function $H_X(x|\pi_x, p_d)$ according to the procedure described in Secs 3 to 6. Only some aspects and results of uncertainty modelling are described in this example. The complexity of such event as UVCE requires an extensive description of modelling accident courses, which lies beyond the scope of the present paper and is envisioned as an individual future paper.

In the present example, the a bivariate exponential distribution was assumed to describe two components of the vector characterising the release, Y . The first component Y_1 is the mean speed of an accidental release of LPG and the second one, Y_2 , is the duration of the release. The epistemic uncertainty in the annual probability of release, p_r , was modelled by means of the random variable P_r obeying a beta distribution with $\alpha = 1,5$ and $\beta = 8$. Five mathematical models were applied to the modelling of accident courses.

The first model $m_1(z_1, \pi_1)$ was used to decide whether the amount of released LPG is sufficient to form a vapour cloud in explosive condition (whether the event E_1 occurs). The second model $m_2(z_2, \pi_2)$ was applied to produce the time history of formation and spreading of vapour cloud. The third and fourth models employed, $m_3(z_3, \pi_3)$ and $m_4(z_4, \pi_4)$, were used to decide whether the vapour cloud is ignited (event E_2 occurs) and, further, whether the energy of an ignition source (primer) initiates a chemical reaction known as detonation (event E_3 occurs). The models $m_1(z_1, \pi_1)$ to $m_4(z_4, \pi_4)$ have been chosen in such a way that if the equality

$$I_1(z_1, \pi_1) \times I_3(z_3, \pi_3) \times I_4(z_4, \pi_4) = 1$$

is satisfied in the j th repetition of the loop B, an occurrence of the explosion (detonation) is modelled in this repetition. Then the number of explosions counted

in the l th run of the loop B is given by

$$n_{dl} = \sum_{j=1}^{n_r} \left(I_1(z_{1j}, \pi_{1l}) I_3(z_{3j}, \pi_{3l}) I_4(z_{4j}, \pi_{4l}) \right).$$

Lastly, the fifth model used in the modelling of accident courses, $m_5(z_5, \pi_5)$, involved a set of formulas relating characteristics of the vapour cloud at the moment of ignition with the ones of the shock front generated by a detonation of the cloud. The characteristics of the vapour cloud expressed by the random vector z_{5j} are distant from the centre of vapour cloud and chemical energy included in the vapour cloud. The characteristics of the shock front, positive peak overpressure x_1 , positive phase impulse x_2 and positive phase duration x_3 , are represented by the vector x_j .

In the course of modelling accident courses the numbers of repetitions, n_p and n_r , were pre-set to be equal 100 and 1×10^5 , respectively. The numbers of detonations counted in respective runs of the inner loop, n_{dl} ($l = 1, 2, \dots, 100$), ranged from 473 to 524. The beta distribution with the estimated parameters $\alpha_e = 1,748$ and $\beta_e = 2350$ was fitted to the sample of frequencies $(n_{dl} \times p_{r,l} / n_r)$ ($l = 1, 2, \dots$).

For brevity sake, the choice of the family of c.d.f.s $F_{X_i}(x|\pi_{x_i})$ ($i = 1, 2, \dots$) is explained here only for the case that the positive overpressure alone, that is, X_1 is of interest for assessment of risks coming from a vapour cloud explosion. This case is urgent when the positive phase duration is greater than the fundamental natural period of structure being analysed [3]. In this case, the family of c.d.f.s $F_{X_{il}}(x|\pi_{x_{il}})$ ($i = 1, 2, \dots$) may be chosen on the basis of 100 samples of positive overpressure, x_{il} ($i = 1, 2, \dots, n_{dl}; l = 1, 2, \dots, 100$).

According to the five-step procedure described in Sec 6, values of x_1 have been divided into 100 categories. Then the percentiles $fr_{c,0,25}$, $fr_{c,0,5}$ and $fr_{c,0,75}$ computed for each category ($c = 1, 2, \dots, 100$). The step curves showing the percentiles are presented in Fig 3. Finally, three complementary c.d.f.s of the lognormal distribution, $1 - F_{X_{il}}(x|\pi_{x_{il}})$ ($i = 1, 2, 3$), have been fitted to the samples. The resulting vectors of parameters, $\pi_{x_{1,i}}$, are

$$\pi_{x_{1,1}} = (0,015 \text{ MPa}; 2,32),$$

$$\pi_{x_{1,2}} = (0,017 \text{ MPa}; 2,37),$$

$$\pi_{x_{1,3}} = (0,019 \text{ MPa}; 3,01).$$

As described above, the confidence in the three c.d.f.s $1 - F_{X_{ii}}(x_i | \pi_{x_{ii}})$ ($i = 1, 2, 3$) may be expressed by the respective probabilities 0,25, 0,5 and 0,25, which have been assigned according to the heuristic rule (4).

8. Conclusions

The paper considers the problem how to choose hazard functions characterising mechanical effects of accidental explosions occurring in consequence of an accidental release of liquefied petroleum gas. A procedure is suggested to assess uncertainties in parameters of the hazard functions. The accidental explosions commonly referred by the abbreviation UVCE (unconfined vapour cloud explosions) have been considered as the factual basis for construction of the proposed procedure.

The procedure consists in a numerical stochastic modelling of accident courses leading to the explosions. The main idea of the present paper is to relate via the stochastic modelling uncertainties in parameters of the hazard functions with lower-level uncertainties in parameters of mathematical models, physical and statistical, describing physical phenomena leading to the explosions. The procedure realises a “loop-in-loop” algorithm wherein the outer loop is used to sample from probability distributions of uncertainties in models’ parameters and the nested loop is applied to sample characteristics of physical phenomena leading to the explosions. An idea is suggested how to choose a family of hazard functions on the basis of the samples of mechanical effects simulated by the procedure suggested.

In the present paper, the consideration “reaches” only mechanical characteristics of the incident blast waves. However, there are no methodological obstacles to generalise the procedure to a modelling of uncertainties related to mechanical characteristics of waves reflected from the mechanical systems being investigated, that is, to dynamic loads imposed on the systems in consequence of an UVCE. The proposed procedure can also be applied to a choice of hazard functions for another kinds of accidental explosions and other adverse mechanical effects, especially in the situations when data from direct measurements of the effects is scarce.

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NEAPIBRĖŽTUMŲ MODELIAVIMAS VERTINANT AVARINIŲ SPROGIMŲ RIZIKĄ PASTATAMS

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S a n t r a u k a

Siūloma procedūra avarinių sprogimų mechaninių poveikių neapibrėžtumams kiekybiškai įvertinti. Nagrinėjamas pavojingasis reiškinys yra dėl avarinių dujų nuotėkių susidarantių degių ir sprogių debesų detonacija ir jos sukeliama sprogimo banga. Sprogimų poveikių intensyvumai yra apibūdinami tikimybinei rizikos analizei įprastomis pavojaus funkcijomis (angl. *hazard functions*). Galutinis siūlomosios procedūros taikymo rezultatas yra pavojaus funkcijų parinkimas statistinių imčių, sukurtų stochastinio modeliavimo būdu, pagrindu. Taikomas Monte Karlo metodas, o modeliuojami nepalankieji reiškiniai, kurių eskalacija baigiasi dujų ir oro mišinio debesies detonacija. Siūlomos procedūros taikymo rezultatai leidžia įvertinti dinamines apkrovas, galinčias veikti tiriamą (vertinamą) konstrukcinę sistemą, įvykus aptariamo tipo sprogimui.

Teoriu požiūriu siūloma procedūra remiasi tikimybinės rizikos analizės metodologija, kuri vadinama klasikiniu Bėjeso požiūriu (angl. *classical Bayesian approach*). Teigiama, kad sprendžiant nagrinėjamą problemą yra sunku išsiversti be Bėjeso požiūrio, nes pavojaus funkcijas tenka parinkti labai ribotos statistinės informacijos sąlygomis. Taikant procedūrą operuojama stochastiniais (angl. *aleatory*) ir pažintiniais (angl. *epistemic*) neapibrėžtumais. Skaičiuojant pagal procedūros algoritmą neapibrėžtumai, susiję su sprogimų pavojaus funkcijomis, yra išreiškiami per „žemesnio“ lygio neapibrėžtumus, apibūdinančius tuos reikškimus, kurių eskalacija gali baigtis sprogimu. Pastebėta, kad šiems neapibrėžtumams kokybiškai išreikšti turima daug daugiau statistinės informacijos, nei neapibrėžtumams, tiesiogiai susijusiems su mechaniniais sprogimo bangos poveikiais konkrečiai konstrukcinei sistemai.

Numatoma praktinio procedūros taikymo sritis yra pavojingųjų dujų ūkio objektų rizikos analizė. Procedūra leidžia įvertinti tų objektų pavojingumą vertinamai (projektuojamai) konstrukcinei sistemai.

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