Cost-effective allocation of safety measures in chemical plants w.r.t land-use planning

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Cost-effective allocation of safety measures in chemical plants w.r.t land-use planning: A Bayesian network formalism

Abstract

Land-use planning (LUP) has widely been employed as a protective safety measure in risk management of major hazard installations such as chemical plants. In the European Union countries, a majority of relevant work over the past years has been inspired by the Seveso II Directive. The inclusion of LUP in the Seveso II Directive has been with the aim of mitigating off-site damage of major accidents on public via setting criteria for (i) the identification of the location and layout of new installations, (ii) the development of existing installations, and (iii) the land developments in the vicinity of existing installations. We, in the present study, have proposed a methodology based on Bayesian network (BN) for cost-effective allocation of safety measures in chemical plants so that both internal and external risks could effectively be mitigated, particularly in compliance with the requirements of LUP. We first employed BN to calculate risks, and then extended the BN to a limited memory influence diagram using additional decision and utility nodes so that it can be used for multi-attribute decision analysis. The development and application of the methodology have been illustrated via fireproofing of a hypothetical fuel storage plant.

Key words: Limited memory influence diagram; Bayesian network; Multi-attribute decision analysis; Land-use planning; Domino effect; Fireproofing.

1. Introduction

The importance of land-use planning (LUP) as a nonstructural protective safety measure in the context of natural hazards has long been recognized by safety experts and risk managers. However, the application of LUP to mitigate the off-site impacts of major technological accidents such as fires, explosions, and toxic gas dispersion is relatively new (Christou and Poerter, 1999; Christou et al., 1999; Laheij et al., 2000; Christou et al., 2006). Early applications of LUP to protect the public from the consequences of major accidents in major hazard installations such as chemical plants in Europe dates back to the 1970s when the Flixborough disaster in 1974 in the UK led to the Health and Safety At Work Act in the same year, requiring industries to keep internal risks (on-site risks) as well as external risks (off-site risks) as low as reasonably practicable (HSE,1989).

The majority of relevant work over the past two decades, however, has been inspired by the EU Council Directive 96/82/EC, also known as the Seveso II Directive. Article 12 of the Seveso II Directive explicitly requires the EU countries to consider LUP for the limitation of the impact of major accidents on residential areas, areas of public use (e.g., schools, airports, stadiums), and areas of particular natural sensitivity and interest (e.g., government buildings, landmarks) (Christou et al., 2006).[1]

As shown in Figure 1, LUP can be considered as a safety element in addition to safe technology, safe management, and emergency planning (Christou and Poerter, 1999; Christou et al., 2006). Safe technology and safe management are mainly aimed at preventing or reducing the probability of major accidents. LUP and emergency management, on the other hand, are aimed at controlling or limiting the consequences of major accidents by decreasing the exposure of the public to dangerous amounts of heat radiation, overpressure, or toxic gas concentration generated by major accidents.

Article 12 has been aimed at setting criteria for (i) the sitting of new installations or the development of existing installations considering nearby existing land developments, and (ii) land developments in the vicinity of existing installations, particularly those developments which would increase either the number or the vulnerability of population at risk. A vast majority of

[1]From June 1st, 2015, the new Seveso Directive III will come into effect in Europe, emphasizing the same LUP requirements asSeveso Directive II.

previous work has been devoted to realize the second requirement; that is, based on the calculated external risks, the land in the vicinity of chemical plants were allocated to particular developments (e.g., to build factories, residential houses, schools) according to their vulnerability and the level of risk (Papazoglou et al., 1998; Laheij et al., 2000; Franks, 2004; Hauptmanns, 2005; Kontic and Kontic, 2009; Taveau, 2010; Cozzani et al., 2014). On the other hand, only a few attempts have been performed to address the first requirement, i.e., considering LUP in the development of existing chemical plants (Papazoglou et al., 2000; Sebos et al., 2010) or in the design (or sitting) of new chemical plants (Bernechea andArnaldos, 2014; Khakzad and Reniers, 2015a).

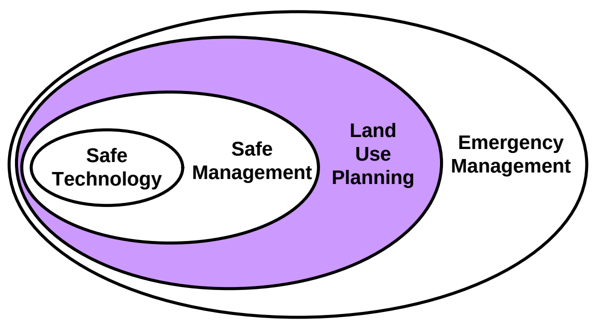

Figure 1. Safety multi-layers as denoted by the Seveso II (Christou et al., 2006).

In the present study, we have introduced a methodology for cost-effective allocation of safety measures in new or existing chemical plants so that not only the LUP requirements can be met but also the level of internal risk can be mitigated. For this purpose, first we use Bayesian network (BN) both to model accident scenarios (including domino effects) and to estimate internal and external risks. The developed BN is then extended to a limited memory influence diagram (LIMID) by adding decision and utility nodes. As a result, both risk analysis and decision making can be performed using the same framework. Considering the cost of safety measures along with their impacts on the amounts of the internal and external risks, the developed LIMID can be used for a cost-effective allocation of safety measures in chemical plants. The outcome of such a cost-effective safety analysis will be an optimal determination of the number and location of safety barriers given a limited budget.

In the next section, the fundamentals of LUP and adapted approaches in chemical plants, particularly the risk-based approach on which the present work is based, are described. After a brief description of BN and LIMID in Section 3, the developed methodology and its application to accident modeling, risk analysis, and decision making will be illustrated through the cost-effective fireproofing of fuel storage plants. The conclusions are presented in Section 5.

2. Land use planning

Several methods have been adapted around the world for LUP: (i) risk-based method, (ii) consequence-based method, and (iii) method of generic distances. These methods are not necessarily contradictory, and in most cases a combination of them are employed. For example in the UK, the consequence-based approach is applied to leakage of toxic gases while the risk-based approach is employed to fire as the dominant accident scenarios in chemical plants (Franks, 2004). Comprehensive reviews and comparisons of LUP methods can be found in Cozzani et al. (2006), Basta et al. (2007), Christou et al. (2011), Demichela et al. (2014), and Pasman and Reniers (2014).

2.1. Risk-based method

Risk-based method includes several steps such as (i) the identification of potential accident scenarios (e.g., fire, explosion, gas dispersion), (ii) the estimation of the probabilities of the accident scenarios, (iii) the calculation of the intensity of physical effects (e.g., heat radiation, overpressure, toxic concentration), (iv) the calculation of the impacts of the physical effects on exposed population, and (v) the analysis of off-site risks in form of individual risk (IR) contours or societal risk curves (F-N curve). Usually quantitative risk analysis methods are applied to steps (i)-(iii) while dose-effect relationships and probit models are employed to step (iv).

Figure 2 shows a safety distance comprising three zones separated by IR contours, resulting from a risk-based approach adopted in the UK (HSE, 2014). The boundaries of the inner zone (IZ), the middle zone (MZ), and the outer zone (OZ) are identified by IR = 1.0 E-05, IR = 1.0 E-06, and IR = 3.0 E-07, respectively (PADHI, 2011). Land use developments inside a safety distance are subsequently identified considering the vulnerability and the number of population at risk. To this end, for example, the UK has defined four levels of land use development (Table 1).

Table 1. Levels defined for land use development based on the number and the vulnerability of population at risk (PADHI, 2011).

Level	Description
1	Factories with limited number of employees
2	Residential houses with limited number of residents
3	Primary schools and nurseries
4	Airports, football stadiums, and large hospitals

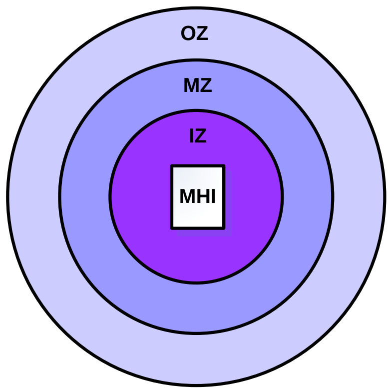

Figure 2. Safety distance around a major hazard installation (MHI), including three zones: inner zone (IZ), middle zone (MZ), and outer zone (OZ) (PADHI, 2011).

Based on the levels in Table 1 and considering the amounts of IR, a decision matrix (Table 2) can normally be used to advise against (AA) or not to advise against (NAA) land developments around a chemical plant. After the Buncefield accident in 2005, an additional zone (DPZ) was also added to the zones in Figure 2, 150 m from the boundary of large-scale petrol storage sites.

Table 2. Decision matrix used in the UK for risk-based LUP (PADHI, 2011). AA: advice against development; NAA: no advice against development.

Levels in Table 1	Zones in Figure 2		
	IZ	MZ	OZ
1	NAA	NAA	NAA
2	AA	NAA	NAA
3	AA	AA	NAA
4	AA	AA	AA

In Canada, a similar risk-based approach has been adapted but with a slightly different criteria for IRs and vulnerabilities. According to Canadian regulation, if IR > 1.0 E-04, no other land use are allowed; if 1.0 E-05 < IR < 1.0 E-04, manufacturing and warehouses are allowed; if 1.0 E-06 < IR < 1.0 E-05, commercial activities, offices, and low-density residential houses are allowed; and if IR < 1.0 E-06, all other land uses such as institutions and high-density residential houses are allowed (Major Industrial Accidents Council of Canada, 1995). Similar risk-based approaches can also be found in other countries around the world.

2.2. Consequence-based method

In the consequence-based approach, a number of credible accident scenarios are determined for a chemical plant. These credible accidents are usually identified using qualitative methods without estimating their probabilities. Then, based on the severity of the consequences a safety distance is determined, comprising two zones. The inner zone represents the area of lethal threshold, Z1, while the outer zone refers to the area of irreversible effect, Z2 (e.g., sever injuries) (Christou et al., 2006). Consequence-based methods are usually applied to situations where either the scarcity or uncertainty of available data does not support a quantitative risk analysis, or where either the density of the exposed population is low or the intensity of physical effects are very high (Franks, 2004).

In the case of having more than one major accident within a chemical plant, whether using a risk-based or consequence-based approach, respective safety distances can be determined for each major accident. Accordingly, if a land development is located within more than one zone, it can be labeled with the most critical zone. In the case of risk-based approach, however, it is also possible to combine IR contours of several major accidents to obtain a unit safety distance for the entire chemical plant under consideration (PADHI, 2011).

2.3. Generic distance method

In the method of generic distances, typical conservative safety distances are usually derived from application of simplified consequence-based approaches. In this method, only the type of industrial activity and the types and the inventory of involved chemicals are taken into account whereas influential factors such as on-site safety measures and the layout of the installation of interest are neglected (Christou et al., 2006). Nevertheless, the application of generic safety distances to LUP is not advised, and should be accompanied by more detailed analyses where practicable.

3. Application of Bayesian network to multi-attribute decision analysis

3.1. Bayesian network

Bayesian network (BN) is a directed acyclic graph (DAG) for knowledge elicitation and reasoning under uncertainty (Pearl, 1988), with a wide variety of applications in risk, safety, and reliability analysis of dependent and complex systems (Khakzad et al., 2011, 2013a,b,c,d; Weber et al., 2012). BN takes advantage of a flexible graphical structure to represent the (causal) relationships among the components of a system using chance nodes and arcs. The type and strength of these relationships are defined using conditional probability tables (CPTs). By taking advantage of conditional independencies resulted from the chain rule and d-separation criteria, BN uniquely factorizes the joint probability distribution of a set of random variables $X = \{X_1, X_2, \ldots, X_n\}$ as the product of the probabilities of each child node conditioned on its immediate parents:

$$P(X_1, X_2, \ldots, X_n) = \prod_{i=1}^{n} P(X_i | \pi(X_i)) \quad (1)$$

where $\pi(X_i)$ is the parent set of X_i. Figure 3 shows a BN comprising four nodes; according to Equation (1), the joint probability distribution of the random variables A-D can be expanded as $P(A, B, C, D) = P(A)P(B|A)P(D|A, B)P(C|D)$.

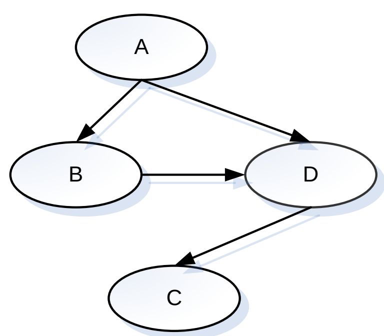

Figure 3. A typical Bayesian network

BN uses Bayes' theorem to conduct belief updating given new evidence E. The evidence can be in the form of knowledge about the one or more chance nodes being in one of its states. Accordingly, the chance node is said to be 'instantiated'.

$$P(X|E) = \frac{P(X,E)}{P(E)} = \frac{P(X,E)}{\sum_X P(X,E)} \quad (2)$$

More detailed information on BN and the exact or approximate solving algorithms can be found in Neapolitan(2003) and Jensen and Nielsen (2007).

3.2. Limited memory influence diagram

BN can be extended to a limited memory influence diagram (LIMID) using two additional types of nodes, *Decision* and *Utility* nodes (Figure 4). Each decision node has a finite set of decision alternatives as its states. A decision node is the parent of all those chance nodes whose probability distributions depend on at least one of the decision alternatives (node D in Figure 4). Likewise, the decision node should be the child of all those chance nodes whose states have to be known to the decision maker before making that decision (node A in Figure 4). Decision nodes are conventionally presented as rectangle while utility nodes as diamond.

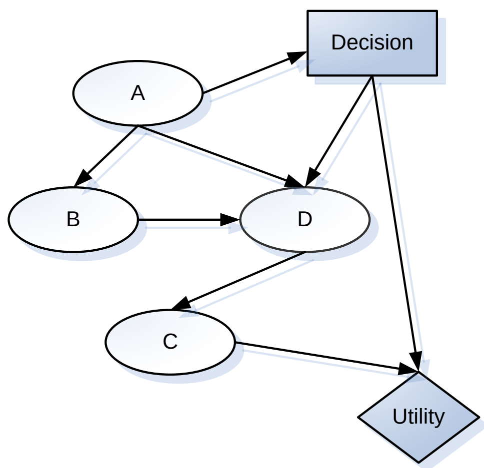

Figure 4. A limited memory influence diagram by adding 'Decision' and 'Utility' nodes to Bayesian network.

A utility node is a random variable whose values (utility values) express the preferences of the decision maker regarding the outcomes of the decision to make. As a random variable, each utility node is assigned a utility table whose values are not probabilities (unlike CPT) but rather numeric values (positive or negative) determined by the decision maker for each configuration of parent nodes, either decision nodes or chance nodes (e.g., the nodes Decision and C in Figure 4) (Jensen and Nielsen, 2007).

For example, considering a set of n mutually exclusive decision alternatives for the node Decision $=\{a_1, a_2, \ldots, a_n\}$ and m states for the node $C = \{c_1, c_2, \ldots, c_m\}$ in Figure 4, the utility table for the node Utility includes n×m utility values $u_{ij} = U(a_i, c_j)$ for combinations of the decision alternatives and the states. Accordingly, the expected utility of the i-th decision alternative, $EU(a_i)$, can be calculated as:

$$EU(a_i) = \sum_C P(C|a_i)U(a_i, C) = P(c_1|a_i)u_{i1} + P(c_2|a_i)u_{i2} + \cdots + P(c_m|a_i)u_{im} \quad (3)$$

As a result, the decision alternative with the maximum expected utility is selected as the optimal decision. Utility values are usually determined by consulting experts and considering the preferences of the decision maker. Utility values can also be generated using appropriate utility functions. A utility function should express how much the decision maker prefers the outcome y1 over y2 considering his attitude towards the decision analysis of interest and also regarding the existing constraints. For a detailed discussion about utility functions see Gilboa (2009).

4. Methodology

To both develop the methodology and demonstrate its application, consider a hypothetical fuel storage plant (Figure 5) which is planned to sit near a residential area and a hospital.

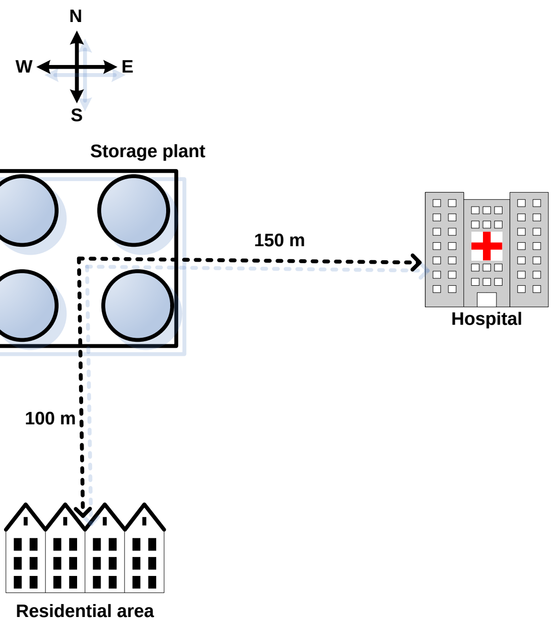

Figure 5. A hypothetical fuel storage plant located 100 m and 150 m from a residential area and a hospital, respectively.

The distances from the centre of the plant to the residential area and the hospital are $100\ \text{m}$ and $150\ \text{m}$, respectively. Furthermore, the plant is required to store $24000\ \text{m}^3$ of crude oil equally in four similar $6000\ \text{m}^3$ atmospheric storage tanks as shown in Figure 5. The storage tanks have a diameter of $30\ \text{m}$ and height of $10\ \text{m}$, and the internal safety distances among them are $30\ \text{m}$ (www.laws-lois.justice.gc.ca). The aim is to find a cost-effective combination of the storage tanks which need to be fireproofed (as an example of the allocation of safety measures) in order to meet the requirements set by LUP and subject to the internal risks and available budget limitations.

4.1. Accident modeling

To estimate internal risks (e.g., damage to the tanks) and external risks (e.g., off-site casualties) posed by the chemical plant in Figure 5 and including them in a cost-effective fireproofing of the storage tanks, the *total probability of accident* for each storage tank (critical unit) should be calculated. The total probability of accident of a storage tank consists of both the probability of its individual accidents and the probabilities of accidents triggered by domino effects (domino-induced accidents) as a result of accidents in the other storage tanks.

Khakzad et al. (2013d) introduced a methodology based on BN to calculate the total probability of accidents in chemical plants with an emphasis on the most probable domino effect originating from a single primary unit. Khakzad and Reniers (2015a) later modified the previous approach such that domino effects with multiple origins can be modeled using a single BN and subsequently be used to estimate the total probability of accidents. In the present work, we employ the methodology developed by Khakzad and Reniers (2015a).

For this purpose, each storage tank in Figure 5 is considered as a critical unit and identified as a chance node as shown in the BN of Figure 6. To draw the arcs of the BN and populate the CPTs, the magnitude of escalation vectors should be calculated. Considering the atmospheric storage tanks containing crude oil, the most credible accident scenario is identified as a major release of crude oil leading to a pool fire given an ignition source. This accident scenario holds for both individual accidents and domino-induced accidents.

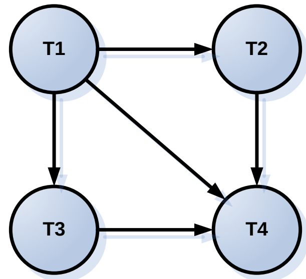

Figure 6. Bayesian network to estimate the accident probabilities of the storage tanks in the plant of Figure 5.

Assuming a wind speed of 10 m/s which gusts from the North West and the stability class of D as the dominant meteorological condition, the magnitudes of heat radiation in kW/m^2 which the tank T_j receives from the tank T_i have been calculated using ALOHA software (www.epa.gov/OEM/cameo/aloha.htm) as listed in Table 3.

Table 3. Magnitude of heat radiation (kW/m^2) T_j receives from T_i.

T_i	T_j				Residential area	Hospital
	T1	T2	T3	T4		
T1	NA	**35.6**	**35.6**	**20.4**	2.4	1.1
T2	10.9	NA	9.6	**35.6**	2.3	2.9
T3	10.9	9.6	NA	**35.6**	11.1	1.1
T4	2.2	10.9	10.9	NA	8.0	2.7

To estimate the probability of pool fire as an individual accident (which can also serve as the primary accident in a domino effect), the probabilities of a major release from a large storage tank ($V \geq 450\ m^3$) and ignition are estimated 1.0 E-04 and 3.0 E-01, respectively (FRED, 2012). Thus, the probability of a pool fire is calculated as 3.0 E-05. Assuming that the dimeter of a major leak (d) would be equal to 0.01 of the diameter of the tank (D) under consideration (e.g., d = 30 cm for a tank of D = 30 m), the diameter of the resulting pool fire would approximately be equal to the diameter of the tank. Moreover, for the sake of simplicity the centers of the tank and the potential pool fire have been assumed to coincide.

Considering a threshold value of $Q_{th} = 15\ kW/m^2$ (Cozzani et al., 2009) for a heat radiation vector to be able to cause credible damage to neighboring storage tanks, those heat radiation vectors whose magnitude are greater than or equal to $15\ kW/m^2$ (bold numbers in Table 3) are added to Figure 6 as the arcs of the BN. In order to calculate the conditional probabilities of damage (domino-induced probabilities) which are used in CPTs, the following probit function can be used (Cozzani et al., 2009):

$$\mathrm{Y} = 12.54 - 1.847 \ln(\mathrm{ttf}) \tag{4}$$

$$\ln(\mathrm{ttf}) = -1.13 \ln(\mathrm{Q}) - 2.67\mathrm{E} - 05\ \mathrm{V} + 9.9 \tag{5}$$

where Y is the probit value; ttf is the time to failure (s); Q (kW/m^2) is the magnitude of heat radiation received by an atmospheric storage tank, and V (m^3) is the volume of the storage tank; the conditional probability of damage can then be calculated using $\mathrm{P} = \varphi(\mathrm{Y} - 5)$ where $\varphi(.)$ is the cumulative density function of the standard normal distribution. Having the probability of an individual pool fire (3.0 E -05) and the probabilities of domino-induced pool fires of a tank of interest linked together using a Noisy-OR CPT (Khakzad et al., 2013d, 2014), the total probability of pool fire in each storage tank can be estimated by solving the BN of Figure 6 in GeNie (www.genie.sis.pitt.edu). Application of the Noisy-OR CPT makes it possible for each single storage tank to get ignited and thus initiating a domino effect.

4.2. Risk analysis

Having the total probability of accident for each storage tank, it is now possible to estimate both internal (e.g., on-site casualties, risk of damage to the tanks, loss of chemical contents) and external risks (e.g., off-site casualties, damage to off-site public assets, damage to the environment). In the present study, for the sake of simplicity, the risk of damage to the storage tanks and loss of their contents is considered as the internal risk whereas the risks of fatalities at the residential area and the hospital are considered as the external risks. The BN of Figure 6 can be extended by adding the node 'Tank damage' to account for the internal risk and the two nodes 'Houses' and 'Hospital' to account for external risks as shown in Figure 7.

Regarding the internal risk, the risk of damage for a storage tank can be calculated as the product of the total probability of accident and the monetary value of the tank, that is, the cost of the tank plus the value of the contained crude oil[2]. It is assumed that during a pool fire the storage tank and the entire oil inventory would be lost. Considering the price of \$372 for 1 m^3 of crude oil

[2] The cost of repair or rebuilding the tank can also be considered when calculating the monetary value of the tank.

(http://www.oil-price.net) and the cost of $570,000 for a 6,000 m³ storage tank (http://www.matche.com/equipcost/Tank.html), the total damage to a storage tank during a pool fire would be about $2,800,000. Thus, as an example, if Tank T1 is on fire but the other three tanks are safe, the amount of the internal risk would be P (T1 = fire, T2 = safe, T3 = safe, T4 = safe) × $2,800,000 = 3.01 E-05 × $2,800,000 = $84. Similarly, the amounts of the internal risk for the other instantiations of the foregoing joint probability distribution can be calculated.

To estimate the external risks, the magnitudes of heat radiation[3] at off-site targets of interest (here, Houses and Hospital) should be determined. Consequently, depending on the type of the target (e.g., building or human) and the level of damage (minor or major damage in case of buildings, and 1st degree burn, 2nd degree burn, or fatality in case of human) a variety of probit functions and dose-effect relationships can be employed to estimate the damage probabilities. In the present study, we consider the probability of fatality for an exposed person (individual risk) as an indicator of the external risk, both at Houses and Hospital.

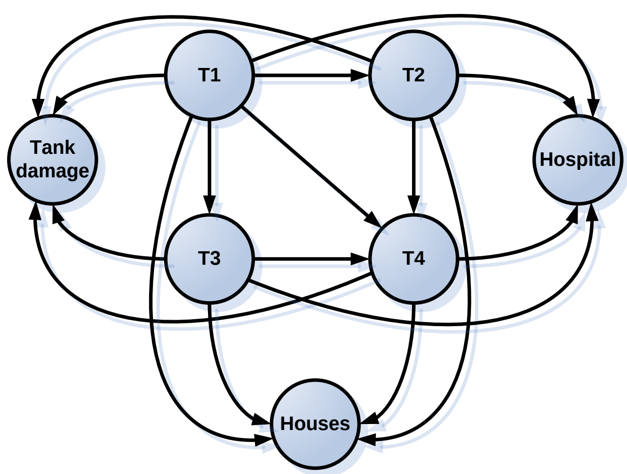

Figure 7. Bayesian network to calculate internal risk (monetary value of tank damage) and external risks (individual risk at Houses and Hospital).

The magnitudes of heat radiation at the locations of Houses and Hospital which have been resulted from pool fires in the storage tanks are listed in the last two columns of Table 3.

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[3] In case of explosion the magnitude of overpressure and in case of toxic gas dispersion the magnitude of gas concentration should be considered.

Subsequently, the probability of death for an exposed person (individual risk) can be estimated using the probit function suggested by Green Book:

$$Y = -36.38 + 2.56\ln(t_{eff}.Q^{4/3}) \quad (6)$$

where t_{eff} (s) represents a human's exposure time to heat radiation (60 s in this study), and Q (W/m^2) is the magnitude of heat radiation received by human. The conditional probability of death given a certain amount of heat radiation can thus be calculated using $P = \varphi(Y - 5)$. For example, according to the BN of Figure 7, the probability of death at the location of Houses given a pool fire in Tank T4 can be calculated as P(T1 = safe, T2 = safe, T3 = safe, T4 = fire, Houses = death) = 1.24 E-05. Similarly, the probabilities of death for the other instantiations of the foregoing joint probability distribution and also the joint probability distribution of Hospital P(T1, T2, T3, T4, Hospital = death) can be calculated.

It is worth noting that Equation (6) is valid for a person exposed to heat radiation in the open while not taking into account the effect of clothing. As a result, this equation tends to overestimate the level of IR as it overlooks the protective influence of buildings and the clothing. Nevertheless, since Equation (6) is being used to calculate IRs at both the houses and the hospital for every single plant layout, such an overestimation would not seem to have a notable effect in the context of risk-informed multi-attribute decision analysis.

4.3. Cost-effective fireproofing

Fireproofing as a passive fire protection measure has been effectively used to prevent or delay the failure of installations and pipelines exposed to fire. Given a primary fire, fireproofing provides extra time to actuate active safety measures (e.g., water sprinkler systems, water deluge systems, blow-down systems), to deploy emergency teams (e.g., firefighting team), and to perform emergency actions (e.g., evacuation of staff, alert local authorities). This is particularly important in the context of domino effect prevention where fireproofing of target installations can provide firefighting teams with sufficient time to suppress or control the primary fire before it can cause the target installations to fail and thus escalating the primary fire to a domino effect.

The successful performance of fireproofing in fire protection, however, depends on several parameters such as the time of delay (td) provided by the fireproofing coating, which is assumed equal to the time to failure of fireproofing coating (Argenti et al., 2014), time for effective mitigation (tem) of the primary fire (Khakzad et al., 2014; Argenti et al., 2014), and the probability of failure on demand and the effectiveness of fireproofing coating (Landucci et al., 2015). Due to costly installation and maintenance expenses, the applications of fireproofing to process plants and offshore facilities have been based on risk-based strategies (Di Padova et al., 2011; Tugnoli et al., 2012). Since the aim of the present study is to develop a general methodology for multi-attribute (cost-effective) allocation of safety measures rather than a detailed study of fireproofing which could be found elsewhere (Argenti et al., 2014; Landucci et al., 2015), the following simplifying assumptions have been made:

(i) The fireproofing effectiveness is 100%, implying that fireproofing coating would be able to successfully prevent the failure of a fireproofed storage tank until it loses its insulating properties which would be equal to td.

(ii) The td provided by fireproofing is long enough to allow the emergency team to suppress the primary fire ($ttf + td > tem$), implying that a fireproofed storage tank is not considered as a target unit and thus not involved in a domino effect.

(iii) The probability of failure on demand of fireproofing coating is zero[4].

(iv) Glass wool is used for fireproofing. The cost of $1\ m^2$ of thermal glass wool ranges from \$0.5 to \$5.0 based on its density ($10 \sim 96\ kg/m^3$) and thickness ($25 \sim 200\ mm$). Assuming that a layer of glass wool ($\$5/m^2$) is used to cover the side area and the roof of a $6000\ m^3$ storage tank (total area of $1650\ m^2$) and considering an installation fee of $\$15/m^2$, the total cost of fireproofing for each storage tank would be $\$33{,}000$.

In order to make a cost-effective decision on how many and which storage tanks to fireproof, the BN of Figure 7 is extended by adding a decision node '$Fireproofing?$' and four utility nodes '$Cost$', '$Property\ loss$', '$Casualty\ 1$', and '$Casualty\ 2$', as shown in Figure 8. The decision node $Fireproofing$ contains $\sum_{i=0}^{4}\binom{4}{i} = 16$ decision alternatives standing for different numbers and combinations of the storage tanks $T1$-$T4$ to fireproof. Consequently, the four aforementioned utility nodes can be used by the decision maker to express his preferences and satisfaction

[4]AIChE (2001) has proposed a probability of 1.0 E-03.

regarding each decision alternative and the ensuing outcomes which are the impacts on the cost (Cost), internal risk (Property loss), and external risks (Casualty 1 and Casualty 2).

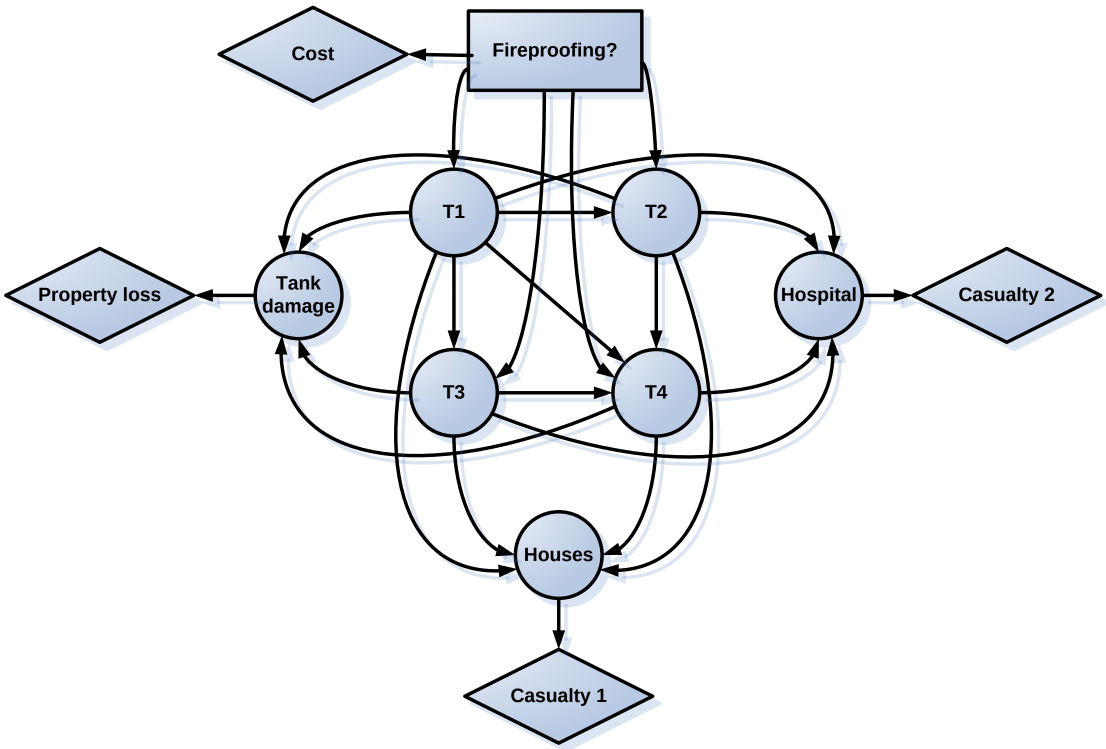

Figure 8. Limited memory influence diagram for cost-effective fireproofing of storage tanks.

As previously mentioned, a utility table is assigned to each utility node. The values in utility tables (i.e., utility values) can be determined either manually or using utility functions. In case of manual identification of utility values, the outcomes of decision alternatives can be compared pairwise and weighted regarding the decision criteria (e.g., available budget, maximum tolerable risk, etc.). The (normalized) eigen vector of the resulted comparison matrix can then be used as utility values explaining the preferences of the decision maker. The same approach is also used in other multi-attribute decision analysis techniques such as Analytic Hierarchy Process (Saaty, 2008). In case of utility function, an appropriate utility function should be able to express how much the decision maker prefers the outcome y1 over y2. Table 4 presents the relations between the two outcomes y1 and y2 and the corresponding utility functions.

Table 4. Relations between outcomes and the corresponding utility functions

Relation	Explanation	Utility function
y1 ~ y2	y1 and y2 are equally preferred	U(y1) = U(y2)
y1 > y2	y1 is preferred to y2	U(y1) >U(y2)
y1 ≥ y2	y1 is at least as preferable as y2	U(y1) ≥ U(y2)
y1 < y2	y2 is preferred to y1	U(y1) <U(y2)
y1 ≤ y2	y2 is at least as preferable as y1	U(y1) ≤ U(y2)

In the present study, we revise a linear utility function introduced by Blank (1980), so that the decision constraints can directly be used in prioritization of outcomes:

$$U(y) = 1 - \frac{y - y_{max}}{y_{max}} \quad (6)$$

where y is the outcome, and y_{max} is the maximum corresponding value. For example, the utility values of the utility node 'Cost' in Figure 8 corresponding to different decision alternatives have been listed in Table 5, assuming a maximum available budget of $y_{max} = \$50{,}000$ for fireproofing. In Table 5, each decision refers to a number of decision alternatives with similar fireproofing costs. For example, the decision 'One tank is fireproofed' refers to: only T1 is fireproofed, only T2 is fireproofed, only T3 is fireproofed, or only T4 is fireproofed.

Table 5. Cost utility values assigned to each decision alternative assuming an available budget of $50,000.

Fireproofing?	Cost ($)	Utility value
No tank is fireproofed	0	2.00
One tank is fireproofed	33,000	1.34
Two tanks are fireproofed	66,000	0.68
Three tanks are fireproofed	99,000	0.02
All tanks are fireproofed	132,000	-0.64

In a similar way, the utility values can be identified for the amounts of internal risk and external risks, assuming $y_{max} = \$500{,}000$ for maximum internal risk, and $y_{max} = 1.0$ E-05 and $y_{max} = 3.0$ E-07 for maximum individual risks at Houses and Hospital, respectively, (HSE, 2014). Having the utility values and the conditional probabilities determined, the LIMID in Figure 8 was then analyzed using GeNie (http://www.genie.sis.pitt.edu) and the values of expected utility for each decision alternative were calculated, as shown in Table 6. As can be seen from Table 6, the decision alternative 'Fireproofing T3 and T4' with the highest expected utility of 6.67 would be the optimal cost-effective decision with regard to the available budget and the maximum acceptable values of the internal and the external risks. Table 7 illustrates the values of individual risks at Houses and Hospital before and after fireproofing of T3 and T4.

Table 6. Values of expected utility for decision alternatives.

Fireproofing?	Expected utility
None	4.26
T1	3.61
T2	3.63
T3	6.05
T4	4.88
T1, T2	2.97
T1, T3	5.39
T1, T4	4.22
T2, T3	5.42
T2, T4	4.23
T3, T4	**6.67**
T1, T2, T3	4.76
T1, T2, T4	3.58
T1, T3, T4	6.01
T2, T3, T4	6.02
All	5.36

Table 7. Individual risks at Houses and Hospital before and after fireproofing of T3 and T4.

Node	Individual risk	
	Before fireproofing	After fireproofing
Houses	3.71E-05	1.26 E-07
Hospital	9.09E-09	3.35 E-09

4.4. Discussion

In the previous sections, we demonstrated an application of LIMID to multi-attribute decision analysis in chemical plants. Since LIMID is an extension of BN, both probabilistic reasoning and decision analysis under uncertainty can be performed using the same framework. In the present study we considered only one decision node and four utility nodes to represent four decision attributes. However, the LIMID shown in Figure 8 can be further extended by adding other decision nodes and utility nodes for a more comprehensive risk management and safety analysis of process plants.

Nevertheless, the application of the developed methodology to large process plants with many critical units needs more elaboration; this is because by increasing the number of critical units (chance nodes) the number of decision alternatives and thus the dimension of CPTs and utility tables may grow exponentially. For example, in case of having five storage tanks in Figure 8 the number of decision alternatives for fireproofing of the tanks would increase from 16 to 32. In cases where a utility node is the child of such a decision node and other chance nodes, the size of the utility table can become very large and intractable. One way to address this problem is to include only those critical units in the process of decision analysis which are making the largest contribution to domino effects and thus the total probability of accident (Khakzad and Reniers, 2015b). These units can be the units which have the most impact on the initiation, continuation, or termination of domino effects (regarding both probability and severity).

Another issue to address in future work is the development of appropriate utility functions. In the present study we, for illustration purposes, employed the same utility function to explain the preferences of the decision maker regarding the cost and the internal risk (monetary values) and the external risks (probabilistic values). However, it should be noted that using the same utility function to weight all decision attributes would imply the decision maker's similar attitude and preferences toward all decision attributes which may not be the case in most multi-attribute decision analysis problems.

Thus, one of the main challenges in the application of LIMID to the cost-effective safety analysis of chemical plants in future would be the developing of effective utility functions. Such utility functions not only should be able to explain the preferences of the decision maker about different outcomes of a decision alternative (e.g., different amounts of fireproofing cost) but also should reflect the attitude of the decision maker towards different decision attributes (e.g., cost vs. risk).

5. Conclusion

In this study we illustrated an application of limited memory influence diagram (LIMID) to multi-attribute decision analysis. To demonstrate the application of the methodology, we employed LIMID to cost-effective allocation of safety measures (fireproofing of storage tanks in this study); for this purpose, the cost of fireproofing, risk of damage to the storage tanks (internal risk) and individual risks (probability of death) at off-site targets (external risks) were considered as the decision attributes. Likewise, the different numbers and combinations of the storage tanks to fireproof were used as decision alternatives. The outcome of such a cost-effective safety analysis is a chemical plant with specific number of fireproofed storage tanks for which the requirements set by available budget, internal risks and external risks (particularly LUP) are effectively met.

The developed methodology can be further extended to incorporate several sequential decisions as well as other influential parameters in the context of LUP risk management and decision analysis. The methodology can readily be employed to analyze the cost-effectiveness of a wide variety of passive, active, and procedural safety measures in chemical plants. Being based on BN, the developed methodology facilitates the inclusion of other factors such as the availability and effectiveness of safety measures in the analysis. However, further work should be carried out to develop appropriate utility functions in order to explain the attitude and preferences of a decision maker towards the cost and effectiveness of safety measure.

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