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Application of Bayesian Network and Multi-criteria Decision Analysis to Risk-Based Design of Chemical Plants

Nima Khakzad*, Genserik Reniers

Safety and Security Science Section, Faculty of Technology, Policy, and Management, TU Delft, The Netherlands
n.khakzadrostami@tudelft.nl

Fires and explosions in chemical plants are still among the major accidents threatening human lives and causing huge asset losses. Although might not completely be eliminated, the risks of such accidents can be reduced by allocating safety measures, applying inherently safer design (ISD) methods, observing land use planning (LUP) regulations, and practicing emergency management. Compared to other risk reduction measures, applications of ISD and, in particular, LUP in chemical plants are new. In most of previous work, however, ISD and LUP have been considered as individual safety elements rather than parts of a coherent safety policy. This, to some extent, arises from contradictory guidelines inferred from the principles of ISD and the requirements of LUP.

The present study aims to employ the principles of ISD and LUP, altogether, in risk-based design of chemical plants so that the levels of both on-site and off-site risks can be reduced as low as reasonably practicable. For this purpose, a Bayesian network (BN) methodology is employed to estimate both on-site and off-site risks posed by potential major accidents in chemical plants. The results of the BN modelling are then used as input data in Analytic Hierarchical Process (AHP), a multi-criteria decision analysis technique, to find an optimal layout for chemical plants of interest. While BN facilitates the incorporation of complicated interdependencies and conditional probabilities encountered in accident analysis and risk assessment, AHP allows considering incommensurate and conflicting decision parameters inevitable in most decision analyses. The outcome of the proposed methodology is an optimal layout for the chemical plant under consideration by taking ISD and LUP principles into account.

1. Introduction

Chemical plants are normally characterized by large inventories of hazardous materials stored in high pressure/high temperature vessels. As such, any uncontrolled or undesired release of hazardous materials in chemical plants which could result in a fire, explosion, or toxic gas dispersion would be able to cause serious on-site and off-site safety risks in terms of human lives, property losses, and environmental damages. Besides, due to the numerousness and complexity of vessels and equipment in typical chemical plants, a primary event such as a fire or explosion which could otherwise be tolerated or controlled is likely to escalate and turn into a major accident by triggering a chain of accidents – also known as domino effect or cascading effect. According to a survey by Darbra et al. (2010), chemical storage plants have been the most frequent sitting impacted by domino effects (process plants are in the second place) while fires have been not only the major cause of domino effects but also the most frequent accident in domino effects. Explosions are reportedly the second major contributor to domino effects while the dispersion of toxic gases is normally not considered due to its inability to trigger other accidents.

Domino effects are among rare events whose consequences could be so severe in terms of fatalities and asset losses. LPG-induced domino effects in Mexico City in 1984 left 650 deaths and 6500 injuries and destructed three process plants. In 2005, a series of explosions at Buncefield Oil Storage Depot in the UK led to a large fire burning for several days, leaving 43 injuries and significant commercial and residential damages. As such, modeling and analysis of domino effects seem inevitable in risk analysis and safety assessment of chemical plants. Although might not completely be eliminated, the risks of domino effects, either on-site or off-site, can be reduced by allocating safety measures, applying inherently safer design (ISD)

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methods, forcing land use planning (LUP) limitations, and practicing emergency management. For example, Articles 9 and 13 of Seveso III – the EU Council Directive 2012/18/EU – explicitly mandates the EU Member States to consider domino effects and LUP for the prevention of major accidents and the limitation of their consequences. LUP requirements in Seveso III (Article 13) mainly include (i) the design of new plants, (ii) the modification of existing plants, and (iii) the land developments in the vicinity of existing plants, particularly those developments which would increase the number or vulnerability of the population at risk. In other words, provision of domino effects in Seveso III has been made to ensure adequate internal safety distances among the units of a plant while the aim of LUP regulations has been to warrant adequate external safety distances between a plant and neighbouring residential areas, areas of public use, or areas of particular sensitivity and interest (Christou et al., 2006).

Nevertheless, applications of LUP and ISD in the design of chemical plants in order to reduce the risks are relatively new (Bernechea and Arnaldos, 2014; Khakzad and Reniers, 2015). In most of previous work, ISD and LUP have been considered as individual safety elements rather than integrated parts of a coherent safety policy. This, to some extent, arises from contradictory guidelines inferred from the principles of ISD and the restrictions of LUP. For example, the principle of 'limit effects' – one of the principles of ISD – is usually realized as adequate internal safety distances among the major hazard installation in a chemical plant in order to prevent the occurrence of domino effects. Considering limited land available for establishment/development of chemical plants in urban areas, however, the longer the internal safety distances the more land will be required for the establishment of a chemical plant and thus the closer the major hazard installation become to the surrounding land developments. In other words, the on-site risks which can be lowered via longer internal safety distances are likely to be compromised by higher off-site risks arisen from the extension of the chemical plant towards the land developments in the vicinity. That is, considering a limited available land for a chemical plant of interest, longer internal safety distances may result in shorter external safety distances.

The present study aims to employ the principles of ISD and LUP, altogether, in risk-based design of chemical plants so that the levels of both on-site and off-site risks can be reduced as low as reasonably practicable. For this purpose, a Bayesian network (BN) methodology is employed to estimate on/off-site risks posed by potential major accidents in chemical storage plants. The results of the BN modelling are then used as input data in Analytic Hierarchical Process (AHP) to find an optimal layout for the chemical plant. While the BN facilitates the incorporation of complicated interdependencies and conditional probabilities encountered in accident modelling and risk assessment, the AHP allows considering incommensurate and conflicting decision criteria inevitable in most decision making problems.

2. Risk-based land use planning

Several methods have been adapted around the world for LUP, including risk-based method, consequence-based method, and 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 in the case of toxic gas leakage while the risk-based approach is employed where fire is considered as the dominant accident scenario (Franks, 2004). Among the aforementioned methods, the risk-based method can be applied not only to a variety of accident scenarios but also to cases in which multiple accident scenarios can be envisaged, facilitating the superposition of risks due to its quantitative formalism.

In risk-based LUP, the magnitude of off-site risks for potential accident scenarios are usually quantified either in the form of iso-risk contours representing individual death probabilities (or individual risk (IR) in brief) or in the form of societal risk (F-N curves). In the former method, based on the magnitude of the iso-risk contours and the number and the vulnerability of the population at risk the land between two consecutive risk contours around the plant is designated to specific developments

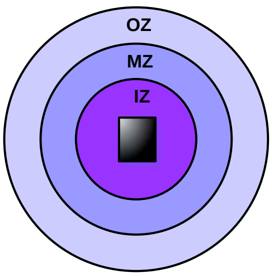

Figure 1: Safety distance around a plant, including three zones: inner zone (IZ), middle zone (MZ), and outer zone (OZ) (PADHI, 2011).

.Figure 1 shows three iso-risk contours circumventing three zones IZ, MZ, and OZ around the chemical plant, adopted from the risk-based LUP approach in the UK (HSE, 2014). The boundaries of the inner zone (IZ), the middle zone (MZ), and the outer zone (OZ) are identified by iso-risk contours associate with IR = 1.0 E-05, IR = 1.0 E-06, and IR = 3.0 E-07, respectively (PADHI, 2011). Considering the number and the vulnerability of population at risk, the land use developments inside each zone can be identified from Table 1.

Table 1: Decision matrix used for risk-based LUP in the UK based on the number and the vulnerability of population at risk (PADHI, 2011). AA: advice against development; NAA: no advice against development.

Level	Land use development	IZ	MZ	OZ
1	Factories with limited number of employees	NAA	NAA	NAA
2	Residential houses with limited number of residents	AA	NAA	NAA
3	Primary schools and nurseries	AA	AA	NAA
4	Airports, football stadiums, and large hospitals	AA	AA	AA

3. Methodology

3.1. Case study

The methodology and its application can be demonstrated through the layout design of a hypothetical chemical storage plant including four similar atmospheric storage tanks, each containing 6000 m^3 of crude oil. The storage tanks have a diameter of 30 m and height of 10 m, with yet unknown internal safety distances, and are to sit on a limited piece of land which is 90 m × 90 m. The centre of the designated land is 100 m from both a residential area and a train station. The aim is to find an optimal layout (optimal values of X ad Y) of the storage plant so that the lowest on-site and off-site risks could be achieved simultaneously. The most credible accident scenario for the storage tanks is determined as a major release of crude oil leading to a pool fire given an ignition source. The probabilities of a major leak and an ignition are selected as 1.0 E-04 and 1.0 E-01, respectively (FRED, 2012). As a result, the probability of a pool fire can be calculated as 1.0 E -05.

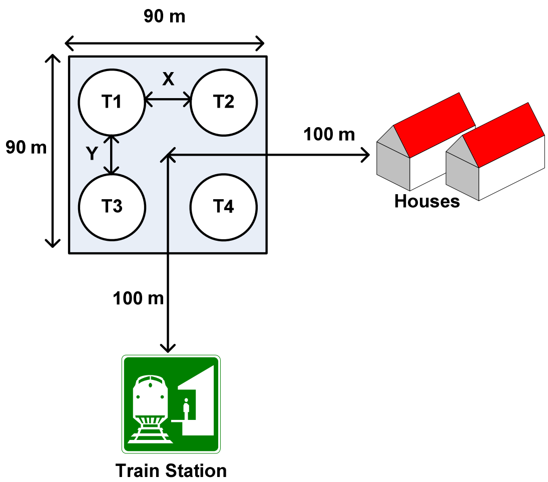

Figure 2: A hypothetical chemical storage plant located 100 m from both a residential area and a train station.

As can be seen from Figure 2, variation of the internal safety distances X and Y has a two-folded contradictory influence on the on-site and off-site risks due to the limited land available. On the one hand, by increasing the internal safety distances the probability of potential domino effects decreases which in turn helps lower the magnitude of on-site risks. On the other hand, by increasing the safety distances the storage tanks become closer to the boundary of the designated land and thus closer to the houses and the train station, posing higher risk (off-site risk) on the population outside the plant in case of a major fire. Multi-criteria decision analysis (MCDA) is a decision analysis technique which allows considering multiple conflicting criteria in decision making. After employing a BN for accident modelling and risk quantification in the next section, we will use AHP, a MCDA technique, in Section 3.3 to address the issue of conflicting decision criteria in the present study.

3.2. Risk analysis

To find the optimal values of safety distances X and Y (decision alternatives) in the present study, a number of decision criteria are needed. For this purpose, we set the on-site risk (internal risk) and the off-site risk (external risk) as the required decision criteria. The on-site risk which is assumed to be equal to the risk of damage to the storage tanks can be quantified as the product of the total probability of accident (Khakzad and Reniers, 2015) and the monetary values of the tanks. The value of a tank can be estimated as the cost of the tank plus the value of the contained crude oil. 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 m3 of crude oil (www.oil-price.net) and the cost of \$570,000 for a 6,000 m^3 storage tank (www.matche.com/equipcost/Tank.html), the total damage to each storage tank during a pool fire would thus be about \$2,800,000.

To calculate the off-site risks, we consider the death likelihood of an exposed person (i.e., IR) at the location of the houses and the train station. To estimate the off-site risks, the magnitude of heat radiation emitted from pool fires at houses and the train station should be calculated. Consequently, depending on the type and the level of damage such as 1st degree burn, 2nd degree burn, or death a variety of dose-effect relationships can be employed to estimate the damage probabilities. In the present study, the probability of death for an exposed person is estimated using the dose-effect relationship suggested in the Yellow Book (Van Den Bosh and Weterings, 1997):

$$\mathrm{Pr} = -36.38 + 2.56\ln(\mathrm{t_{eff}}\,\mathrm{Q}^{\frac{4}{3}}) \quad (1)$$

Where Pr is the probit value; $\mathrm{t_{eff}}$ (s) represents a human's average exposure time to heat radiation (60 s in this study), and Q (W/m^2) is the magnitude of heat radiation received by a human. The conditional probability of death given a certain amount of heat radiation can thus be calculated using $\mathrm{P} = \varphi(\mathrm{Pr} - 5)$. φ(.) is the cumulative density function of the standard normal distribution. Following the BN methodology originally developed by Khakzad et al. (2013) and modified by Khakzad and Reniers (2015), the BN to estimate the total probability of accident and quantify the on/off-site risks can be presented in Figure 3.

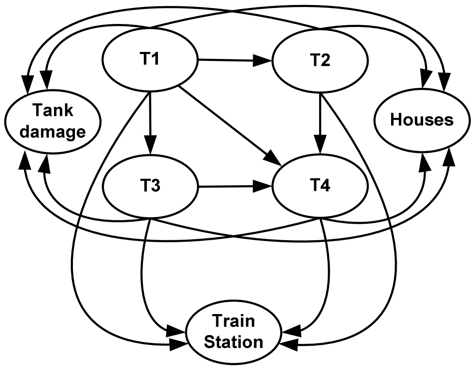

Figure 3: Bayesian network to calculate on-site and off-site risks.

The total probability of accident of a storage tank consists of both the probability of its individual accidents and the probability of accidents triggered by potential domino effects (domino-induced accidents). To develop the BN in Figure 3, each storage tank in Figure 2 is presented as a chance node (nodes T1-T4). To draw the arcs of the BN and quantify the conditional probabilities, the magnitudes of heat radiation between each pair of storage tanks should be calculated for different combinations of the safety distances X and Y. The values of X and Y used in this study are listed in Table 2 (columns 2 and 3). Moreover, we assume a wind speed of 10 m/s gusting from the NW, ambient temperature of 15^{o} C and the stability class of D as the dominant meteorological condition. Accordingly, if the magnitude of heat radiation (kW/m^2) which a tank receives from another tank is greater than the threshold value of Q_{th} = 15 kW/m^2 (Cozzani et al., 2014) an arc is drawn from the emitting tank towards the receiving tank, implying that the pool fire in the former tank can cause a credible damage to the latter tank. The conditional probability of damage then can be calculated using Eq (2) (Cozzani et al., 2014):

$$\mathrm{Pr} = 12.54 - 1.847(-1.13\ln(\mathrm{Q}) - 2.67 \times 10^{-5}\mathrm{V} + 9.9) \quad (2)$$

where Pr is the probit value, Q (kW/m^2) is the magnitude of heat radiation, and V (m^3) is the volume of the storage tank; similar to Eq (1), the conditional probability of damage or domino-induced accident probability can then be calculated using $\mathrm{P} = \varphi(\mathrm{Pr} - 5)$. Having the probabilities of individual accidents (1.0 E-05 as calculated in Section 3.1) and probabilities of domino-induced accidents, the total probability of pool fire for each storage tank can be estimated by solving the BN in GeNie (www.genie.sis.pitt.edu). Having the total probability of accident for each storage tank, it is now possible to estimate both on-site and off-site risks by adding the nodes Tank damage, Houses, and Train Station to Figure 3. The magnitudes of on-site and off-site risks have been listed in Table 2.

Table 2: Layout characteristics and associated on-site and off-site risks.

Case No.	X (m)	Y (m)	On-site risk: Tank damage ($)	Off-site risk: Houses (IR)	Off-site risk: Train station (IR)
1	10	10	563	1.40 E-05	1.40 E-05
2	10	20	490	1.03 E-05	1.38 E-05
3	10	30	481	8.31 E-06	1.57 E-05
4	20	10	490	1.38 E-05	1.03 E-05
5	20	20	417	1.10 E-05	1.10 E-05
6	20	30	405	1.41 E-05	9.25 E-06
7	30	10	481	1.57 E-05	8.31 E-06
8	30	20	405	9.25 E-06	1.41 E-05
9	30	30	395	1.23 E-05	1.23 E-05

3.3 Multi-criteria decision analysis: an optimal layout

AHP (Saaty, 2008) is a technique for MCDA, consisting of m decision criteria {C_1, C_2, …, C_m} and n decision alternatives {A_1, A_2, …, A_n}. Decision criteria are decision parameters based on which the decision alternatives are being compared pairwise and weighted. Likewise, the decision criteria can be of different or similar weights based on the preferences of the decision maker. The weights are usually assigned based on a fundamental scale table (Saaty, 2008), ranging from 1 to 9. The results of the pairwise weighting are populated in respective matrices. The normalized elements of the principal right eigenvector of each matrix represent the local weight of each decision criterion/alternative. The global weight of the i-th decision alternative, A_i, can subsequently be calculated as the summation of the product of the local weight of the decision alternative and the global weight of each decision criterion:

$$\alpha_i = \sum_{j=1}^{m} \theta_j \beta_{ij} \qquad (3)$$

where α_i is the global weight of the i-th decision alternative, A_i; β_{ij} is the local weight of i-th decision alternative considering the j-th decision criterion, C_j; θ_j is the global weight of the j-th decision criterion. Accordingly, the decision alternative with the highest global weight is selected as the optimal decision alternative. In the present study we assume, for illustrative purposes, that the all three decision criteria, i.e., the on-site risk (i.e., Tank damage) and the off-site risks (i.e., IR at the locations of houses and train station) are of the same importance; that is, θ_j = 0.33 for j = 1,2,3. As such, the optimal decision is a plant layout with values of safety distances for which the magnitudes of the on-site risk is the lowest while the magnitudes of the off-site risks at the houses and the train station are 1.0 E-05 and 1.0 E-06 at the highest (see Section 2), respectively. However, it should be noted that in the case of conflicting decision criteria, which is the case in the present study, an optimal decision is less likely to satisfy all decision criteria.

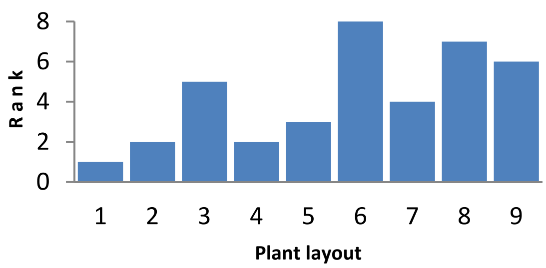

Figure 4: Final ranks of the case numbers listed in Table 2.

Applying AHP analysis, the global weights of the decision alternatives (the nine cases in Table 2) have been calculated as α_i= {0.030, 0.066, 0.132, 0.066, 0.109, 0.175, 0.122, 0.168, 0.135}; the final ranks of the decision alternatives are displayed in Figure 4. As can be seen, the case number 6 (X= 20 m, Y= 30 m) has the highest rank (highest global weight) compared to the other alternatives.

4. Conclusions

In this study we demonstrated an application of Bayesian network and Multi-criteria decision analysis to risk-based design and decision making in chemical plants. Considering the on-site risk (damage cost to process equipment) and off-site risks (individual death likelihoods for population with various vulnerability and locations) as decision criteria, we employed a Bayesian network methodology previously developed by Khakzad and Reniers (2015) to quantify the decision criteria for each decision alternative; the decision alternatives are nine similar layouts of a chemical storage plant each of which with different internal safety distances. Limiting the magnitude of the on-site risk to the lowest and the magnitudes of the off-site risks to the maximum values defined by land use planning requirements, we applied Analytic Hierarchical Process to compare and rank the decision alternatives. As a result, an optimal plant layout was designed (selected among the available alternatives) in which both the concepts of inherently safer design and the regulations of land use planning were effectively taken into consideration.

The present study illustrated the practicability and efficacy of BN-AHP in risk-based design of chemical plants. Nevertheless, it should be noted that the efficiency of the proposed methodology can further be improved by considering internal safety distances of finer increments (we used an increment of 10 m). This, however, could have resulted in higher number of decision alternatives which in turn would make the process of comparison and weighing too cumbersome and intractable (the maximum number of decision alternatives advised in AHP is nine). Even with a coarse increment for safety distances, the number of decision alternatives could rise exponentially in case of more complex layouts. This in turn would limit the applicability of AHP to risk-based design of complex chemical plants. To address this issue, we propose using the non-linear goal programming or game theory in future work.

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