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# Risk-based design of process plants with regard to domino effects and land use planning

Nima Khakzad[a,*], Genserik Reniers[a,b,c]

[a] Safety and Security Science Group (S3G), Faculty of Technology, Policy and Management, TU Delft, Delft, The Netherlands
[b] Antwerp Research Group on Safety and Security (ARGoSS), Faculty of Applied Economics, Universiteit Antwerpen, Antwerp, Belgium
[c] Research Group CEDON, Campus Brussels, KULeuven, Brussels, Belgium

## HIGHLIGHTS

- A Bayesian network methodology has been developed to estimate the total probability of major accidents in chemical plants.
- Total probability of accidents includes the probability of individual accidents and potential domino effects.
- The methodology has been extended to calculate on-site and off-site risks.
- The results of the risk analysis have been used in a multi-criteria decision analysis technique to risk-based design of chemical plants.

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## ABSTRACT

Land use planning (LUP) as an effective and crucial safety measure has widely been employed by safety experts and decision makers to mitigate off-site risks posed by major accidents. Accordingly, the concept of LUP in chemical plants has traditionally been considered from two perspectives: (i) land developments around existing chemical plants considering potential off-site risks posed by major accidents and (ii) development of existing chemical plants considering nearby land developments and the level of additional off-site risks the land developments would be exposed to. However, the attempts made to design chemical plants with regard to LUP requirements have been few, most of which have neglected the role of domino effects in risk analysis of major accidents. To overcome the limitations of previous work, first, we developed a Bayesian network methodology to calculate both on-site and off-site risks of major accidents while taking domino effects into account. Second, we combined the results of risk analysis with Analytic Hierarchical Process to design an optimal layout for which the levels of on-site and off-site risks would be minimum.



## 1. Introduction

Early applications of LUP to major accidents in Europe dates back to the early 1970s when the Flixborough disaster in 1974 in the UK led to the Act 1974, requiring industries to keep internal risks (on-site risks) as well as external risks (off-site risks) as low as reasonably practicable [17]. Accordingly, local planning authorities have been obliged to obtain advice from HSE in the case of land developments around major hazard installations (MHIs) [14,18,17].

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 Seveso Directive II. Articles 8 and 12 of the Seveso II explicitly mandates the EU Member States to consider domino effects and land use planning, respectively, for the prevention of major accidents and the limitation of their consequences to man and the environment. Article 12 is mainly devoted to (i) sitting of new installations, (ii) modification to existing installations, and (iii) land developments in the vicinity of existing installations, particularly those developments which would increase either the population at risk or the severity of the risk. In other words, it does not apply to an existing installation unless there are any internal modifications to the plant or external land developments in the vicinity of the plant.

Provision of domino effect in Seveso II has been made to ensure adequate internal safety distances among the units of a MHI where it is possible that a major accident in a unit propagates to neighboring units, triggering other secondary accidents. Likewise, requirements of LUP have been included in Seveso II to warrant

* Corresponding author.
*E-mail address:* nkhakzad@gmail.com (N. Khakzad).

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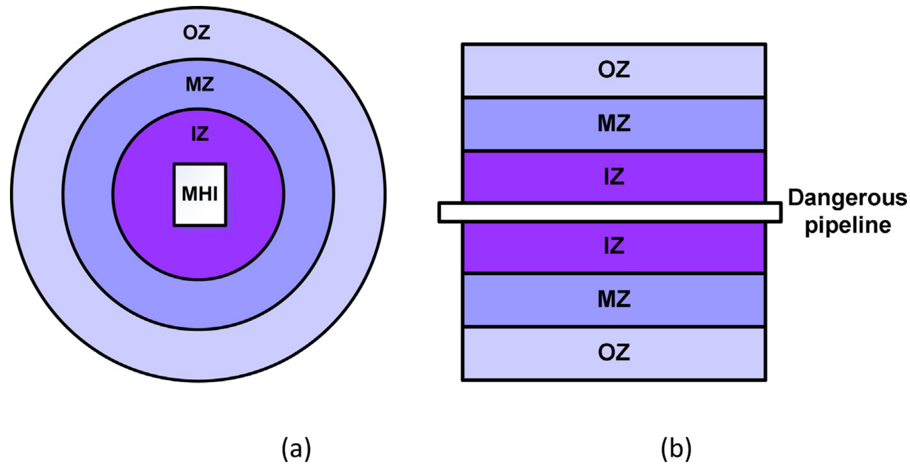


**Fig. 1.** Buffer zone around a major hazard installation (a) and a pipeline (b) [23].

adequate external safety distances between a MHI and residential areas, areas of public use, or areas of particular natural sensitivity and interest [7]. From 1 June 2015, the new Seveso Directive III comes into force in Europe, containing the same LUP philosophy as its predecessor Seveso II.

LUP has traditionally been considered from two perspectives: (i) land use development in the vicinity of an existing MHI and (ii) modification/development of an existing MHI considering nearby existing land developments. From the first perspective, off-site individual risk or societal risks are calculated for an MHI considering major accident scenarios [22,31,16,11,21]. Accordingly, pieces of land in the vicinity of MHI are designated to particular developments based on their vulnerability and the levels of risks they are exposed to. The role of domino effects (chain of accidents), however, has barely been considered in the calculation of off-site risks [11].

According to the second perspective, however, LUP requirements have been considered in multi-criteria decision analysis (MCDA) in order to develop or modify existing MHIs [25,30,4] such that the modifications would decrease or at least not increase the level of off-site risks. In the previous attempts, however, either the effect of domino effects has been neglected (e.g. [25]) or the total risk comprising on-site and off-site risks has been considered as a single decision criterion (e.g. [4]). While the ignorance of domino effects could result in underestimation of accident probabilities and thus the value of risk, aggregation of on-site and off-site risks into a single risk value could significantly overshadow the requirements of LUP in the decision analysis. For example, a plant with a lower aggregate risk is likely to be chosen over another plant with a slightly higher aggregate risk even if the former plant might have violated the LUP obligations.

The present study to some extent belongs to the second perspective in the sense that it considers LUP requirements to design (not develop or improve) an optimal layout for an MHI. To overcome the drawbacks of previous work, the impact of domino effect is explicitly included in the risk analysis of major accidents, and instead of aggregating on-site and off-site risks; a MCDA technique, Analytic Hierarchical Process (AHP), is employed to account for on-site and off-site risks as separate decision criteria. Thus, it would be possible to prioritize plant layout alternatives and choose the one which best meets the constraints of the problem without compromising off-site risk for on-site risk or vice versa. To calculate the on-site and off-site we modify a Bayesian network (BN) methodology introduced by Khakzad et al. [19]. The application of the developed BN in conjunction with AHP to risk-based design of chemical plants is demonstrated via a fuel storage plant.

## 2. Risk-based land use planning

Several methods have been adapted around the world to implement LUP such as the method of generic distances, consequence-based method and risk-based method. These methods are not necessarily contradictory, and in most cases a combination of them are employed (hybrid methods). Comprehensive reviews and comparisons of conventional LUP methods adapted within European countries have been discussed by Papazoglou et al. [24], Christou et al. [6,8], Cozzani et al. [9], Basta et al. [3], Demichela et al. [12], Pasman and Reniers [26].

The risk-based method includes several steps: (i) to identify and estimate the probability of potential accident scenarios, (ii) to identify and estimate the intensity of physical effects[1] (e.g., heat radiation, overpressure, toxic concentration), (iii) to estimate the adverse effects of the physical effects on exposed population, and (iv) to analyze off-site risks in form of individual risk (IR) contours or societal risk curves (F–N curve) [7]. Quantitative risk analysis methods are usually applied to estimate the probabilities of potential accidents while dose-effect relationships and probit models are used to estimate the adverse effects of the physical effects on off-site targets (usually human).

Fig. 1 depicts a buffer distance comprising three zones separated by IR contours, resulting from a risk-based approach adopted in the UK. Circumventing an MHI (Fig. 1(a)) or a hazardous pipeline (Fig. 1(b)), the boundaries of the inner zone (IZ), the middle zone (MZ), and the outer zone (OZ) are identified by IR contours corresponding to $10^{-5}$, $10^{-6}$, and $3 \times 10^{-7}$respectively [17,23]. Land developments inside a buffer zone should be limited according to the magnitude of IR and vulnerability and number of population at risk. To this end, for example, the HSE of the UK has defined 4 levels of vulnerability for land developments: level 1 including factories with limited number of employees; level 2 including residential houses with limited number of residents; level 3 including primary schools and old people homes; and level 4 including football stadiums and large hospitals.

Based on these vulnerability levels and amount of IRs, the following decision matrix (Table 1) can be used to Advise Against (AA) or Not to Advise Against (NAA) land developments [23].

[1] In the case of off-site risk analysis, the physical effects are also referred to dangerous doses if they result in distress of all population, medical attention of a majority or hospitalization of a minority of people, or fatality of 1% of population.