IMPLICATIONS OF THE UNCERTAINTIES PRESENT IN RISK ASSESSMENT OF CHEMICAL INSTALLATIONS TO RISK-INFORMED DECISION MAKING: THE CASE OF LAND-USE PLANNING

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ABSTRACT

This paper deals with the uncertainties present in the results of risk assessment of chemical installations and it examines their implications to land-use planning decisions. In particular, the results from the EU funded research project ASSURANCE are used as a case-study. Three types of land use planning approaches are considered, namely, a "consequence-based" approach, a "risk-based" using only individual risk criterion, and a "risk-based" approach using both individual risk and societal risk criteria. The analysis demonstrates that the land-use planning decisions are significantly affected by the uncertainties in the assessment of both the consequences and the frequencies of the potential accident scenarios.

1. INTRODUCTION

Among the variety of decisions that can and must get a significant input from risk assessment, those related to Land Use Planning (LUP) in the vicinity of hazardous industrial establishments are probably the most important and the most difficult ones. Land-use planning decisions have always been an issue of conflict among various objectives and interests, influenced by different stakeholders, including the plant operators, the authorities and the general public. The role of the latter has been recognised and expanded in the recently issued framework European Directive for control and management of industrial hazards, the Seveso II Directive. In fact, not only land-use planning provisions are included in the Directive, posing a clear obligation to planning authorities to consider major accident hazards in the planning process, but also a requirement is put for consultation of the public in land-use and off-site emergency planning. Moreover, the involvement of many actors and the implications of the relevant decisions on the exploitation of a scarce good, such as land, make the decisions difficult.

The importance given by the society and the existing legislation on risk considerations in land-use planning, enhances the role of Quantitative Risk Assessment (QRA) as a main input in the decision making process. It also poses an increased demand for accuracy in the results, together with transparency and defensibility of the decisions. However, the process itself of carrying out a QRA is linked with several uncertainties, originating either from the stochastic nature of the introduced parameters, or from imperfect knowledge of the physical phenomena following an accidental release, or finally from expert judgement and simplifications made in the calculations throughout the assessment. These uncertainties include data sources, handling of stochastic variables like meteorological conditions, source term definitions, modeling of physical phenomena, and vulnerability calculations. As QRA results are used as input in land-use planning (among other) decisions, these decisions are also affected by the uncertainties present in risk assessment.

This paper examines the implications of the uncertainties in risk assessment to land-use planning decisions. The work is based on the results of a European project on the ASSessment of Uncertainties in Risk ANalysis of Chemical Establishments (ASSURANCE) [1, 2]. The project aimed at identifying the uncertainties associated with Risk Analysis of major industrial hazards and assessing the way these uncertainties can affect the final outcome of risk studies and of the relevant decisions based on that outcome. In order to achieve this goal, a number of benchmark exercises / case studies have been performed by the partners and the results are analysed in a modular and structured way. A reference plant served as the basis for a realistic description of these case studies. For this particular project an ammonia storage plant was selected, consisting of cryogenic and pressurised storage tanks, together with import loading/unloading facilities and the relevant piping. This installation was analysed independently by each partner, using common input data and boundary conditions, but varying methods, tools and assumptions. The results were then compared and discrepancies are identified, discussed and explained. The results and conclusions of the project are discussed in another paper to be presented in the 2001 ESREL Conference (see [1]) and in the Final Report of the project ([2]), while herein we are dealing with the effects of the uncertainties in consultation and safety distances and other LUP decisions, in general.

In order to assess the impact of the uncertainties on land-use planning decisions, the results calculated by different partners and the distances/areas corresponding to given threshold levels of consequence, dose or risk, are compared. The variation in the predicted distances/areas clearly shows the effect of uncertainties in land-use planning.

2. LAND USE PLANNING APPROACHES AROUND CHEMICAL SITES

From the methodological point of view, two main approaches are followed in the European Union for land use planning purposes[1]: the first focuses on the assessment of consequences of a number of conceivable scenarios and can be typically called "*consequence based*" approach, and the second on the assessment of both consequences and probabilities of occurrence of the possible accident

[1] For a detailed review of the methodologies for LUP the reader can refer to Ref. 3, 4 and the sources therein.

scenarios and can be called "*risk based*" approach[2]. For a given installation, the "consequence based" approach gives the consequence area for lethal effects and serious injuries resulting from the scenarios assessed, while the "risk based" approach gives an area within which there is a given probability of a specified level of harm resulting from a large number of possible accident scenarios. Concerning the risk based methodologies, a further distinction can be done between those using mainly *individual risk based criteria* (e.g. UK) and those using both individual and *societal risk criteria* (e.g. the Netherlands).

Various criteria are in use to determine the safety distances/areas: In the "consequence based" approaches, the $LC_{1\%}$ (concentration lethal to 1% of the general population), AEGL (Acute Exposure Guideline Levels) and IDLH (Immediately Dangerous to Life and Health) concentration levels are used. In the "risk based" approaches, the 10^{-6} individual risk level, and a certain line in the F-N curve representing the maximum tolerable societal risk are in use. Tables 1 and 2 give examples of such criteria according to the Dutch (risk based) and the French (consequence based) LUP system, respectively. Here it should be noted that all methodologies consider indirectly the density of population in the surroundings of the establishments; however, the Dutch approach is the only one using a *formal criterion* in order to express the public aversion against accidents with increased number of casualties.

Furthermore, new approaches have been proposed for taking societal risk into account using a simplified method [5], for taking multiple and conflicting objectives into account [6-9], and for integrating the results from multiple risk sources into overall area risk indices [10, 11]. In the following, three indicative philosophies of LUP are examined, which broadly correspond to the national policies of three E.U. countries (France, UK, and the Netherlands), and the discrepancies in LUP decisions due to Risk Assessment results are discussed.

Table 1. Example of probabilistic risk criteria: The Dutch risk acceptability criteria

	Individual risk criteria	*Societal risk criteria*
Existing installations	10^{-5} per year	$10^{-3}/N^2$
New installations	10^{-6} per year	$10^{-3}/N^2$
Negligible risk	Always ALARA* applied	Always ALARA* applied

* ALARA : As Low As Reasonably Achievable

Table 2. Example of consequence based criteria: Ammonia concentration levels and corresponding damaging effects, as used in the French planning system.

Concentration level	*Exposure time*	*Effect on humans*
6200ppm	30 min	The LC_1 contour (1% Lethality of the general population or 10^{-2}death risk)
1000ppm	3 min	IDLH (dose equivalent to 500 ppm for 30 minutes)

[2] "Generic" distances, based on the type of the hazardous activity or on a broad estimation of the consequences of typical / "standardised" installations, are also in use; however, their use is restricted in deriving "consultation distances" which provide a first assessment of the compatibility of the installation with the surrounding uses of land.

3. THE CASE STUDY

To illustrate the above-mentioned approaches of LUP, the case study of the ASSURANCE project is used. The seven European Institutes / partners in the benchmark exercise, together with the risk analysis that they produced with their own methodology (at least the ones who have followed a quantitative risk assessment), have also analysed eleven reference scenarios, as these scenarios were set by the French partner as the most significant for this installation according to the French approach.

The reference scenarios chosen for common analysis were the following:

- *Scenario 1*: Full section rupture of 8'' ammonia feeding pipeline.
- *Scenario 2*: Full section rupture of 4'' pipeline in the ammonia refrigerated plant.
- *Scenario 4*: Full section rupture or disconnection of the connecting flange on the liquid phase between ammonia ship and unloading arm.
- *Scenario 7*: Full section rupture of 10'' pipe on the discharge line of a pump in the cryogenic section.
- *Scenario 7**: Rupture of a ship tank.(Two partners did not consider this scenario)
- *Scenario 9*: Catastrophic rupture of the cryogenic ammonia storage tank.
- *Scenario 10*: Full section rupture of a 20''distribution line in the cryogenic section.
- *Scenario 14*: Catastrophic rupture of one pressurized ammonia tank.
- *Scenario 15*: Full section rupture of the distribution line of a pressurized ammonia tank.
- *Scenario 17*: Full section rupture or disconnection of the connecting flange on the liquid phase between ammonia truck and unloading arm
- *Scenario 18*: Catastrophic rupture of an ammonia truck tank (pressurized).

All teams but the French one have performed two types of calculations with these scenarios:

a) Full Quantitative Risk Analysis for the determination of both individual and societal risk, taking into consideration weather and other types of uncertainty and
b) Selected runs (with each partner's toxicological data) for the predefined concentrations (see Table 2) attained in the various scenarios by the released clouds of ammonia under two sets of meteorological conditions, namely wind speed 5m/s and atmospheric stability class D and wind speed 2m/s and atmospheric stability class F.

Calculations supporting a "consequence based" LUP approach

According to a "consequence based" approach, the maximum distances (endpoints) attaining the damaging effects of Table 2 have been calculated by all partners and for all Reference Scenarios (see also the ASSURANCE project report [2]). Table 3 presents these endpoints to lethality and irreversible effects thresholds for weather conditions F2 (stability F and wind speed 2m/s, which is the less favorable case), and for Scenario 7*, as the worst case. However, as it is discussed in [1] and [2], this scenario represents the maximum discrepancy in the results, since the knowledge of the Risk Assessment community in modeling the release of liquid ammonia onto water surface and the subsequent dispersion is not consolidated yet. Moreover, since this scenario was not analyzed by all partners, it seems more appropriate to consider also the "second worst" scenario, which is Reference Scenario 14 (catastrophic rupture of a pressurized tank). The relevant endpoints are then presented in Table 4. Tables 3 and 4 give also the average distances, the deviation of the assessment of each partner from the average, and the mean square root variation, R.

Tables 3 and 4 show a great discrepancy in the results and the distances calculated by the partners, ranging for Ref.Sc.14 from –62% up to +156% of the average for the lethal effects endpoint, and from –70% up to +92% for the irreversible effects endpoint. In other words, this discrepancy means that the planner should establish a first (lethal effects) zone of 570m based on the results of partner P5 or a zone of 3800m based on the results of partner P3. It is also worth noting that the variation in the results is reduced for long distances (less variation in the assessment of irreversible effects zone).

Table 3. Variation in concentration endpoints for Reference Scenario 7*

Partner	*6200 ppm endpoint (m)* **Distance corresponding to criteria for first death**	*Deviation from Average (%)*	*1000 ppm endpoint (m)* **Distance corresponding to criteria for first irreversible effects**	*Deviation from Average (%)*
Partner 1	2845	-39.3	10150	51.0
Partner 2	65	-98.6	68	-99.0
Partner 3	10000	113.2	10000	48.8
Partner 4		/		/
Partner 5	540	-88.5	3390	-49.6
Partner 7	10000	113.2	10000	48.8
Average	***4690.0***	***R=4436.4 (94.6%)***	***6721.6***	***R=4210.0 (62.6%)***

Table 4. Variation in concentration endpoints for Ref.Sc.14

Partner	*6200 ppm endpoint (m)* **Distance corresponding to criteria for first death**	*Deviation from Average (%)*	*1000 ppm endpoint (m)* **Distance corresponding to criteria for first irreversible effects**	*Deviation from Average (%)*
Partner 1	1650	11.2	6350	25.8
Partner 2	820	-44.8	1510	-70.1
Partner 3	3800	156.0	9700	92.2
Partner 4	1360	-8.4	3150	-37.6
Partner 5	570	-61.6	1510	-70.1
Partner 7	705	-52.5	8063	59.8
Average	***1484.2***	***R=1102.3 (74.3%)***	***5047.2***	***R=3190.2 (63.2%)***

Calculations supporting a "risk based" LUP approach employing an individual risk criterion

The QRA results are summarized in the isorisk curves. Figure 1 gives an example of the discrepancy in individual risk calculations, presenting the "minimum" and "maximum" isorisk curves (those corresponding to minimum and maximum area) for a level of individual risk 10^{-5} per year.

In order to compare the isorisk curves assessed by each partner, the area within each curve has been calculated and the "average" radius, i.e. the radius of a circle equivalent to this area, has also been calculated. Table 5 presents the average radii of the areas covered under isorisk curves 10^{-5} and 10^{-6} per year of QRA results for each partner. Deviation from the average has been calculated and appears in the Table, too.

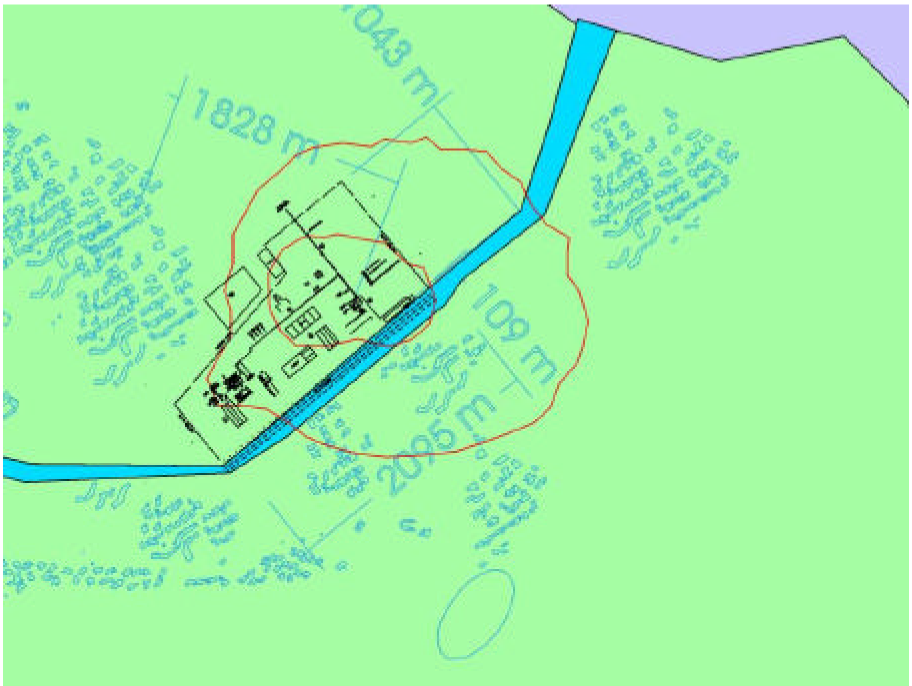

Figure 1. Discrepancy in the results of individual risk calculations relevant to risk-informed Land Use Planning: Maximum and minimum distances for the isorisk curve 10^{-5} yr^{-1}

Table 5. Variation in the average radius for Isorisk Curves 10^{-5} and 10^{-6} per year				
	Average radius for 10^{-5} yr^{-1} Individual Risk Curve		**Average radius for 10^{-6} yr^{-1} Individual Risk Curve**	
PARTNER	**Radius(m)**	*Deviation from Average (%)*	**Radius(m)**	*Deviation from Average (%)*
Partner 1	565	-8.13	1325	12.36
Partner 2	125	-79.67	925	-21.56
Partner 3	1310	113.01	1676	42.13
Partner 4	545	-11.38	820	-30.46
Partner 5	530	-13.82	1150	-2.48
Partner 7	/*		/*	
Average	***615***	***R=384 (62.46%)***	***1179.2***	***R=304 (25.79%)***

* Results of Partner 7 are not comparable to the others

As previously in the "consequence based" approach, significant variation is reported. The variation is however lower in longer distances (as it was the case with the results of Tables 3 and 4). More specifically, the equivalent "distance" for 10^{-6} yr^{-1} individual risk ranges from 820m to 1676m, i.e. from –30% to +42% of the average. It is thus expected that a planner using the Dutch individual risk criteria (for new installation; for existing installations the 10^{-5} criterion is followed) be confronted with this range of results. The same variation will be present if a planner decides to use the UK criteria and needs to calculate the "middle" zone.

Calculations supporting a "risk based" LUP approach employing both individual risk and societal risk criteria.

The results of the assessment of societal risk are summarized in Figure 2 (partner P6 did not perform probabilistic calculations). It has to be stressed that the calculations were based on fictitious population data, exaggerating the population density close to the plant, contrary to the practices in all European countries. The purpose for using such data was to reveal differences and variations in the results, which otherwise could remain hidden. Consequently, the societal risk is high, indeed much higher than the criterion F-N curve of $10^{-3}/N^2$ (see Table 1). All partners therefore agree that the fictitious installation is above the tolerable limits. However, significant discrepancy is again present in the results since, for example, the number of people affected in a single accident at a frequency of 10^{-5} ranges from 20 to 2000 people, according to the calculations of the partners (the "acceptable" value according to the criterion curve would be 10 people). Even if the most conservative assessment of partner P3 is excluded from the data-set, the remaining results would range from 20 to 200 people.

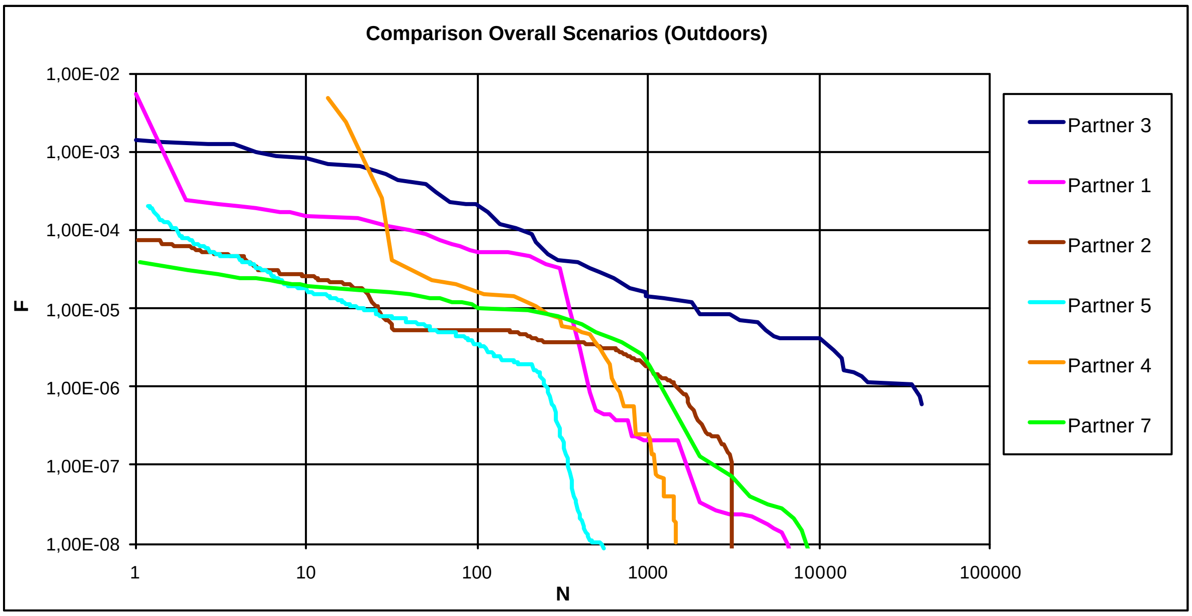

Figure 2. Discrepancy in societal risk calculations (based on fictitious population data)

4. CONCLUSIONS

As the public concern about the protection of human life and the environment increases and the land use planning restrictions remain one of the most important controls for managing major accident hazards, the application of the various approaches for LUP and the comparison between them becomes one of the most widely discussed issues. It is a general impression – and the results herein can demonstrate it – that most often the "consequence based" approach produces longer distances. However, such a comparison in order to be meaningful should take into account the overall application framework: What scenarios are taken into consideration? What restrictions apply? What happens when a criterion is not fulfilled? Which other measures are taken in order to ensure the safety of the citizens and the environment? What is the general philosophy for applying one or the other method?

All these questions have to be addressed and taken seriously into consideration in an overall comparison of the LUP approaches. Such a comparison, however, was out of the scope of this paper. What is discussed herein is the effect of uncertainties in risk assessment and modeling on the relevant Land Use Planning decisions. And, as it was demonstrated above, the effect of the uncertainties is very strong, producing great discrepancies in the relevant decisions. In fact, the discrepancy produced by the Risk Assessment results can be greater than the one produced by the type of methodology applied. Finally, it should be underlined that great variations in the results supporting LUP decisions are reported both in the application of the "consequence based" and in the application of the "risk based" approach (see also Ref.[12]).

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