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The control of major accident hazards: The land-use planning issue

Michalis D. Christou [a,*], Aniello Amendola [a,1], Maria Smeder [b]

[a] *European Commission, Joint Research Centre, Institute for Systems, Informatics and Safety, Ispra, I-21020 (Va), Italy*

[b] *Swedish Rescue Services Agency (Räddningsverket), S-65180 Karlstad, Sweden*

Abstract

Land-Use Planning with respect to major accident hazards constitutes one of the new requirements of the 'Seveso II Directive'. The paper discusses the rationale and the requirements set by the Directive for the operators of the plants and the planning authorities to take into account the major accident hazards in the land-use planning procedure. Then, the paper focuses on approaches and criteria applied in the European Union, and gives information on procedures in other countries, wherever available. The approaches analysed are grouped into three broad categories, namely, establishing 'generic distances', 'consequence based', and 'risk based'. Finally, two illustrative examples facilitate understanding and comparison of the analysed approaches. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Accidents such as those in Bhopal and Mexico City tragically demonstrated how the consequences of accidents could be severely aggravated by the proximity of dangerous sites to areas with high population density. Following these accidents, the reviewing process of the 'Seveso Directive' (82/501/EEC) [1] resulted in the inclusion of requirements on siting and land use planning (LUP) in the new directive [2].

In reality in most European Countries certain legislative prescriptions (mostly based on the Napoleonic code) already existed to separate certain industrial facilities from

* Corresponding author. Tel.: +39-0332-789-516; fax: +39-0332-789-007; e-mail: michalis.christou@jrc.it

[1] Presently visiting the International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria.

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neighbouring developments, and regulatory urban plans distinguished between 'industrial zones' and other land uses. However, despite this, demographic pressure led to gradual creation of high-risk situations.

The concern and awareness of the authorities on LUP is clearly expressed both in the early attempts to establish risk tolerability criteria and in the performance of a number of area risk studies. Some of these studies in Europe include the ones performed in the Rijnmond area (Netherlands) [3,4], the Canvey Island (UK) [5,6], the Trieste area (ARTIS project, Italy) [7] and the Ravenna area (ARIPAR project, Italy) [8,9]. All of these studies aimed at the assessment of risk in the area concerned and almost always the results were used for Land-Use Planning purposes and/or in order to support the establishment of general decision criteria.

On the other hand, major accidents in fixed installations are not the only hazards for which LUP is necessary. Other kinds of hazards linked with possible air, soil and water pollution due to continuous emissions or waste production are regulated by different legislation (such as the one on Environmental Impact Assessment) when siting new potentially noxious and polluting facilities such as waste treatment plants. These issues have extensively been analysed in the literature (see, for example, the works of Kunreuther et al. [10,11], Derby and Keeney [12], Petts and Eduljee [13]). Transportation of hazardous materials and linked temporary storage (e.g. marshalling yards, docks) may also present hazards of major accidents, in certain cases with severity comparable to that of accidents originating from fixed installations. For that reason it has also been subject of different studies and concerns (see Hubert and Pages [14], Mansot [15], Health and Safety Commission [16]). The paper will not discuss LUP criteria for transportation accident hazards, since transportation is outside the scope of the Seveso-II Directive, even if hazards related to temporary storage were proposed to be covered by the European Commission [17] (for a discussion on this issue see the proceedings of an EC seminar on the subject [18]). However, the Seveso II obligations to consider accident hazards in LUP might start a process among the planning authorities which in the long term could generally result in taking into account transportation risk in an appropriate manner. At the same time, 'responsible care' programmes have been voluntarily adopted by the chemical industry for transport accidents prevention, and for co-operation to emergency preparedness and response.

The scope of the present paper is to highlight the main characteristics of Land-Use Planning with respect to major accident hazards posed by fixed installations and to review the approaches followed not only across Europe but also world-wide. Focus is given to the decisional approaches adopted and basic criteria, rather than to aspects such as legislation and procedures followed. It should be stressed from the beginning that the amount of available information is not uniform for all countries. Some countries have already established well-structured procedures for taking major hazards into account in the land-use planning process. Others are very close to establishing procedures and criteria, while others have not yet any specific legislation for taking major accident hazards into account in the land-use planning process.

It should be underlined that the paper aims at providing insights on the principles and the rationale behind the use of each method and all discussions serve this purpose. In no case does the paper aim at a comparison between existing criteria leading to a recommendation on the 'best' or the 'optimum' approach to be followed. It should be recalled that behind each approach there is a legislative style, which derives from a long history and national cultural development.

2. Land use planning as a multi-dimensional decision process

There is no doubt that establishments able to cause major accidents under certain circumstances with consequences extending outside their borders should be separated from residential and commercial areas by *adequate* distances.

In principle, separation distances should be long enough to ensure the safety of humans and sensitive environment. However, land is an economic good, generally characterised by scarcity in Europe. Therefore, there is a need for establishing adequate separation distances which satisfy some sustainability principles. The 'adequacy' may then depend both on the source of risk (the installation itself, the substances involved, the technology employed and the management systems), and on the vulnerability of the environment affected by a potential accident. It is expected that the separation distance established around a small gas station would significantly differ from the distance around a large hydrogen fluoride production unit. In a similar way, it is expected that hospitals and areas populated by sensitive and disabled people will be located in safer places than workplaces, where a limited number of healthy working people are present during part of the day. Also these distances may vary according to the socio-economic context into which risk is perceived and evaluation criteria are developed, and whether alternative activities/land uses are available.

In establishing an appropriate new LUP policy, a major problem is how to cope with the historical legacy of incompatible development. Any legislative or regulatory decision should consider in a different way the historical heritage and future developments. The provisions should however be developed in such a way that in the long term the existing risk situations could be mitigated in a way as much as possible similar to the new situations. This might be achieved when major modifications in an existing establishment are treated in a similar way as 'new establishment', thus decreasing risk to the neighbourhood each time new investments are made; and similarly by considering restructuring, restoration, change of use of old developments around hazardous sites as far as sustainable in agreement with the new LUP policy.

In general, the scope and objective of Land Use planning in the vicinity of hazardous installations is thus to ensure that the likelihood and the consequences of the potential accidents are taken into consideration when decisions are made concerning:

- siting of new installations;
- extension (or modifications) of existing installations;
- determination of uses of land in the vicinity of establishments;
- proposal for new developments in the vicinity of establishments.

There is a number of questions related to the above mentioned decisions. The question of proper *siting* of a chemical facility—or the equivalent question of its *licensing*, given that a decision on its location has already been made—is clear enough. *Modifications* of existing establishments usually imply quantitative and/or qualitative modifications in the profile of risk, thus affecting all subsequent decisions. The *determination of uses of land* in the vicinity of establishments handling hazardous materials presents another side of the problem, where control is applied on the receptors of risk. Setting adequate *separation distances* around such establishments, together with the well-known practice of *zoning*, are without doubt addressed by the same question. Decisions on the *extension of housing areas* towards an existing chemical establishment are also included in the same framework. Last but not least, the establishment of risk *tolerability criteria* is closely connected with the LUP problem.

Another topic in which the correct Land-Use Planning can be of great importance is the 'domino effect'. The escalation of an accident across neighbouring process units and plants can be avoided by adequately siting the relevant installations and planning the uses of land around them.

In all the relevant discussions the socio-economic implications of any decision should not be underestimated. In general, it would not be practical to react to the lack of planning by radical and sudden measures, such as an indiscriminate relocation of existing establishments, demolition of residential buildings, or extreme restrictions to the modifications of existing buildings extended also to houses' repair.

From the above discussion it is clear that Land Use Planning is a decision problem of conflicting objectives. On one hand there is the attempt to provide maximum safety to the surrounding population and on the other, the desire to exploit in the best possible way the land, thus obtaining the maximum benefit from its exploitation. Other considerations, mainly of socio-economic character, such as employment opportunities, importance of the establishment for the national economy, and benefits for the local community from the operation of the plant, constitute additional objectives. Moreover, the *involved parties* including industry, authorities, employees, the population and groups of interest bring at the stake different priorities and values to be taken into account in the decision process.

3. Provisions of the Seveso II Directive for Land-Use planning

The new Directive 96/82/EC ('Seveso II') [2] in Article 12 requires the following.

- That the Member States shall ensure that the objectives of preventing major accidents and mitigating the consequences of such accidents *are taken into account* in their land use policy and especially through controls on the siting of new establishments, the modifications to existing ones, and new developments (residential areas, areas of public use, transport links, etc. [2]) in the vicinity of existing establishments.

[2] The Directive does not give a definition of 'transport links'; nor have the activities of the working group for establishing guidance on LUP (see below in the same section) addressed the question yet. The interpretation of the term might be manifold: the most natural one might be to consider new transportation routes in the proximity of hazardous establishment in the same way as 'location frequented by the public' which might be a target of an accident. But also the relevance (either beneficial or adverse) of a new transport route vs. emergency planning and response should be considered. Of course new transport links serving an existing installation should also be considered as an important modification of the establishment according to the definitions of Art. 3 of the Directive.

- That their land-use policy takes account of the need to establish and maintain *appropriate separation distances* between the establishments covered by the Directive and residential areas, areas of public use and areas of particular natural sensitivity or interest.
- That the land-use policy takes account of the need for additional technical measures in existing establishments so as not to increase the risk to people. [3]
- That all competent authorities and planning authorities shall set up appropriate *public consultation procedures* to facilitate the implementation of the LUP policies mentioned above.

It should be noted that the Directive does not make any attempt in quantifying the separation distances in detail. On the contrary, it allows the Member States and the competent authorities to quantify them and to decide what distance would be appropriate for each establishment. The competent authorities of each Member State are also responsible for setting up procedures facilitating the implementation of the land-use planning policies. It is recognised here that it is not possible to have a unique procedure for all Member States, the political, cultural, structural, technical and other differences being a parameter of distinction. Moreover, these procedures should be designed in such a way as to ensure that technical advice on the imposed risk is available and will be used when decisions are taken. This advice can be either on a case-by-case or on a generic basis. A European Commission Technical Working Group has been set up in order to provide help and guidance to the competent authorities of the Member States in complying with Article 12. The guidance is expected to be published by the time the Directive has been implemented by the Member States (February 1999), and will refer both to the use of existing technical approaches and to procedural issues. The reader is invited to refer to this guidance for an update of the criteria and approaches which are in use.

The criteria and approaches, which will be described in the following, have been developed with respect to risk for people. Risk to the environment should also be considered by an adequate LUP policy, and environmental compatibility criteria are being proposed by several environmental agencies (see for instance the paper by Slater and Jones in this same issue). An extensive discussion of the issue has not yet started among the parties in the relevant working groups. The Directive focuses on the areas 'of particular natural interest or sensitivity', which should be understood as area such as those with protected fauna and flora, species threatened by extinction, important water resources. For existing installations their protection can be ensured by the measures described in [3].

[3] Again the Directive does not define what should be meant as 'additional technical measures', but the meaning should be clear when considering that this requirement is intended to stand for existing installations, in cases where adequate spacing between establishments and developments cannot be maintained. In such a case mitigation can be obtained by compensating technological measures (e.g. double containment, decrease of inventories, new process (inherent-safe) design, additional safety/mitigation systems like water curtains). In certain cases particular measures should be considered even for protection of ecologically sensitive areas, which because of a previous inadequate LUP are threatened by industrial activities. The necessary technical measures should be identified after the analysis of the safety report including the assessment of risk to man and environment.

For the siting of new establishments it might be advantageous if the planning authorities could consider the environmental hazards of accidents together with the environmental impact due to continuous emissions (Environmental Impact Assessment) in order to have an integrated assessment of the environmental compatibility of the proposed activity. This would also call for an increased co-operation between the regulatory and control agencies dealing with environment and those dealing with safety.

Also the transnational LUP implications are worthy of discussion. As far as this issue is concerned, Seveso II Directive has to be complemented by the UN-ECE convention on transboundary effects of accidents [19]. [4] Article 13 of the Directive states that "Member States shall, with respects to the possibility of a major accident with transboundary effects originating in an establishment under Article 9, provide sufficient information to the potentially affected Member States so that all relevant provisions contained in Articles 11 (Emergency Planning), 12 (LUP) and this Article (Information on safety measures) can be applied, where applicable, by the affected Member State."

The information on risk of existing establishment given by the Country originating the risk should be sufficient to allow the Country affected to elaborate its own Land Use control according to the procedure established for that Country. Even the decision-making on new siting is included under Article 13. However, in this case the UN-ECE Convention is more explicit under both its Article 7 (Decision Making on Siting) and under its Article 9.2 which states: "The Party of origin shall... give the public in the areas capable of being affected an opportunity to participate in relevant procedures with the aim of making known its views and concerns on prevention and preparedness measures, and shall ensure that the opportunity given to the public of the affected Party is equivalent to that given to the public of the Party of origin". This might imply a transboundary risk communication problem, which in certain cases would bring to contrast risk criteria and procedures, which are adopted in the neighbouring countries. A discussion of this particular issue is outside the scope of the present paper; the subject, however, would be of interest for an empirical research based on case studies on transboundary area administrative arrangements and analysis of linked decision-making.

4. Review of commonly used approaches for Land-Use Planning

4.1. Overview

Risk Assessment in its broad definition is a structured procedure to evaluate qualitatively and/or quantitatively the level of risk imposed by the hazard sources identified within the installation. The purpose of Risk Assessment is to provide the necessary input to a variety of decisions. Among these decisions, the ones related to Land-Use Planning are obviously of great importance, and risk as a factor is, or at least should be, one of the main parameters. Consequently, the selection of a specific method,

[4] See also the paper by W. Kaiser and M. Schindler in this issue, pp. 59–75.

completeness and accuracy for Risk Assessment can heavily affect the outcome of the decisions to be taken.

In the European environment, any attempt to establish guidelines on Land-Use Planning should certainly take into consideration the significantly different national legislation that exists in the various Member States and the practices used. At the moment there are broadly speaking

- countries which have already established well-structured procedures for taking major accident hazards into account in land-use planning, and
- countries in which such procedures are under development, and no explicit regulations for land-use planning in the vicinity of hazardous installations exist up to now.

The Netherlands, UK, France and, to some extent, Germany, have already developed comprehensive LUP procedures. Southern European countries, such as Italy, Greece, Spain and Portugal, belong to the second category, while some countries as Denmark are very close in establishing procedures and criteria for land-use planning. Such Member Countries do not show less concern about major hazards but the control of land-use planning in the vicinity of hazardous installations is covered up to now by the legislation for physical planning and consists of procedures in which accident hazards are not explicitly considered in land use policies. However, in view of the Seveso II requirements, specific and explicit new regulations are currently under development.

From the methodological point of view, two approaches adopted for risk assessment can be distinguished in the EU: the first focuses on the assessment of consequences of a number of conceivable event 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 event scenarios and can be called 'risk based' approach. For a given installation, the 'consequence based' approach will characteristically show the consequence area for lethal effects and serious injuries resulting from the scenarios assessed, while the 'risk based' approach will show an area within which there is a given probability of a specified level of harm resulting from the large number of possible accident scenarios.

In addition to these two methodological approaches, a third one could also be distinguished; this consists of the determination and use of 'generic' distances depending on the type of the activity rather than on a detailed analysis of the specific site. These safety distances usually derive from expert judgement and are mainly based on historical reasons, the experience from operating similar establishments, or the environmental impact of the plant.

It should be noted that the above categories are not mutually exclusive. Each Member State can be characterised by the approach adopted within the following list of four cases [20–24]:

- establishing 'generic' distances, mainly based on experience and the environmental impact of industrial activities;
- the 'consequence based' approach;
- the 'risk based' approach, and
- arrangements still in the development phase.

Table 1 summarises this classification. For each country it is indicated whether the 'generic safety distances', the 'risk based' or the 'consequence based' approach is

Table 1
Brief overview of the land-use planning practices in the European Union

Country	'Generic' safety distances	'Consequence based' approach	'Risk based' approach	Land-use planning criteria	Arrangements still being developed
Austria					X
Belgium		X (Walloon)	X (Flemish)		X
Denmark					X
Finland		X			
France		X		X	
Germany	X	X		X	
Greece					X
Ireland					X
Italy					X
Luxembourg		X		X	
The Netherlands			X	X	
Portugal					X
Spain		X			X
Sweden	X	X			X
The United Kingdom			X	X	

followed and whether criteria related with the level of risk or consequences have been adopted or arrangements are under development or included in the general land-use planning legislation.

The amount of information available about the methodologies in those countries, which have already finalised LUP criteria, is much more elaborated. For this reason the methodologies elaborated in these countries will be presented in more detail in the following.

4.2. *'Generic' safety distances*

The development and use of generic safety distances is based on the principle that uses of land which are not 'compatible' with each other should be separated with separation distances. The extent of this separation zone is assumed to depend only on the type of industrial activity or on the quantity and type of the hazardous substances present. In order to assist the implementation of the approach, a number of tables have been elaborated which classify the industries into categories, and for each category a separation distance is proposed. Both 'broad' and 'fine' categories are reported to be in use. The broad categories, e.g. 'inorganic chemical industry', make no distinction between the substances used or between the quantities of the substances present. Fine categories on the other hand are used in order to determine the activity precisely, and take into account the quantity of substances present and other characteristics in the determination of the adequate separation distance (e.g. LPG spheres, located above the ground, with a capacity between 200 and 500 m^3). However, the design characteristics, safety measures and particularities of the establishment under question are not taken into account.

The safety distances mentioned above usually derive from expert judgement and are based on historical data, the experience from operating similar plants, rough consequence estimates or on the environmental impact of the plant. It is clear that the operation of certain industrial activities and of the chemical industries in particular, apart from the hazards imposed to the public, is usually associated with a number of additional noxious characteristics. These characteristics include noise, odour and routine emissions. Without doubt, separation distances should exist between these industrial areas and areas of different activities—mainly, residential areas—to ensure that population will not be affected from these noxious characteristics. In practice in this case it is implicitly assumed that if adequate protection has been achieved against these noxious characteristics, this protection extends and covers accident hazards of the industry as well. From a historical point of view, the 'generic' distances approach is connected to the concept of practically 'zero risk'. According to this principle—which is a vital point in the legislation of some countries—no residual risk is allowed to be present outside the borders of the chemical installation. In other words, it is supposed that the measures taken by the operator and supervised by the authorities create a sufficient number of barriers to make it practically impossible for the occurrence of major accidents with consequences outside the establishment fences. It is recognised that not all the hazardous activities have additional noxious characteristics, such as noise and odour, e.g., activities with explosives. In these cases the separation distance derives from past experience, from simple models calculating the effects of major accidents, or even because of historical reasons.

It should be stressed that 'generic' distances appear to be very useful when a formal Risk Assessment—or Consequence Assessment—is not available. In such cases this method can at least provide a certain separation between the developments and the hazardous activity. Concerning the principles of the approach, they are conceptually close to the traditional perspective of the land-use planner, who is confronted with two conflicting activities, the industrial and the residential, which do not fit with each other and should be separated by some separation distance. The length of this distance is usually estimated mainly from the noxious characteristics deriving from the continuous activity and at a second stage from the imposed hazards. The consequences of a 'worst' or 'conceivably bad' scenario are then calculated but no reference is made to the likelihood of such scenario.

The use of generic safety distances is mainly adopted in Germany and Sweden and it has been proposed as an adequate approach to be followed in Austria. In Germany [20,22,25–27], the uses of land have been classified into categories, and areas of different categories should be separated by safety distances. In addition, the basic concept of the risk assessment methodology and the LUP criteria adopted are such that the installation should be established and operated so that *no risk* is imposed to man or the environment outside. More importance is thus given on safety precautions and measures on site, and these are taken into consideration when deciding on the siting of major hazard installations. It is also expected that the separation distances be based on noxious characteristics other than risk. If the hazard of the installation has to be assessed (due to absence of noxious characteristics), the approach adopted is the 'consequence based' one, taking into account factors such as the maximum credible amount of the substance, its temperature and pressure and the vulnerability of the surroundings. Generally applicable scenarios are not used, with the exception of the storage of LPG and explosives, for which respectively a BLEVE and the explosion of a quantity of isolated stored explosives, are considered as the worst credible events.

In Sweden, guidelines on land use planning have been produced on similar principles [28,29]. The safety distances are based on effects from normal emissions (e.g. noise, smell and continuous emissions of chemicals) and not on risk or consequences of major accidents. For many cases however, the safety distance from the accident point of view is considered to fall within the recommended safety distances. It should be noted, however, that the 'generic' distances calculated this way serve as input values for further discussions in each specific case. Risk assessment can also be performed from which separation distances are calculated on the basis of the expected consequences. The establishment and use of criteria referring to the risk based approach has however been examined in a recent study [30].

4.3. The consequence based approach

The 'consequence based' approach (for which sometimes the term 'deterministic approach' is used) is based on the assessment of the consequences from the conceivable accidents, whereas no attempt is made to quantify the likelihood of these accidents. The concept behind the use of this approach is to avoid tackling the uncertainties related to the explicit quantification of the frequencies of occurrence of the potential accidents. It should be noted that the assessment of the frequencies of occurrence of the various accidents is a hard and time-consuming task, and much criticism has been expressed on the usefulness of the assessed frequencies, given the uncertainty associated with the final estimations.

In a sense, the 'consequence based' method has a rationale similar to the 'worst conceivable scenario' approach (in which, however, the worst conceivable scenario is not determined by the worst possible case, but implicit consideration of likelihood is taken, as will be explained later). The underlying philosophy is based on the idea that if there are enough measures to protect the population from the worst conceivable accident, enough protection will also be provided for any accident, less bad than the 'worst'. Therefore, this method evaluates only the extent of the accident, and not the likelihood of its occurrence. The criticism of the method underlines the difficulty in selecting the basic accidents; in fact, accidents believed to be the 'worst' were shown in some cases to result in less consequences than others, initially judged as more severe.

For tackling the problem of identification of the 'worst conceivable' scenario, the method of 'reference scenarios' has been developed and is widely used in France. In order to get a license for operating an installation, the plant-owner has to evaluate the consequences deriving from a number of accidents (reference scenarios), and to prove that all the adequate measures have been taken to minimise this hazard. These scenarios are defined from experience and mainly from historical data for the specific type of plant. However, the list is neither exhaustive nor exclusive. The authorities may require the evaluation of additional scenarios, according to their judgement. The reference scenarios are well defined and the consequences resulting from them are thoroughly estimated. Then, the 'worst' scenario is identified and taken into account for planning purposes.

The extent of consequences provides a measure of the severity of the potential accidents independently of their likelihood of occurrence. These are used as a criterion in the 'consequence based' approach. The consequences of the accidents are taken into consideration quantitatively by estimating the distance in which the physical magnitude describing the consequences (e.g. toxic concentration) reaches a threshold value corresponding to the beginning of the undesired effect (e.g. fatality). Various threshold values are in use, for example:

- the IDLH (Immediately Dangerous for Life and Health), ERPG-2 (Emergency Response Planning Guideline), LOC (Level of Concern), LC1% (Lethal Concentration), the concentration corresponding to the 'first death' (lethality 1%), for toxic releases;
- the thermal radiation corresponding to 3rd degree burns (e.g. 5 kW/m^2), for thermal effects;
- the overpressure corresponding to eardrum rupture (e.g. 140 mbar), for explosions.

In addition to the distance corresponding to a 'lethal' threshold value of the physical magnitude describing the consequences, another distance is sometimes estimated, corresponding to the beginning of 'irreversible' effects. This latter distance is used for separation of areas with sensitive population (e.g. schools, hospitals) or very densely populated areas from the hazardous source.

The 'consequence based' approach is adopted in France and the French-speaking region of Walloon, in Belgium. Slightly different approaches based on the same principles have been proposed in several other countries. [5]

4.3.1. Example of use: France

In France, the operator of an establishment is required to evaluate the consequences of a number of scenarios, which then serve as a reference for the determination of protection zones around the installation. The reference scenarios are based on analysis of past accidents as well as on possible events. There are six main scenarios referring to

[5] The approach followed in the USA for emergency planning and communication to the public can broadly be considered as belonging in the above category [31]. According to the accidental release provisions of the Clean Air Act, regulated sources are required to conduct hazard assessment, including offsite consequence analysis, and report the results in the Risk Management Plan (RMP). This consequence analysis is based on a worst-case scenario and a number (at least one) of alternative release scenarios. The worst-case release is defined as the release of the largest quantity of the substance, determined taking into account only 'administrative' measures (e.g. partial filling of vessels), from a vessel or process line failure that results in the greatest distance to a specified endpoint. This endpoint usually corresponds to the ERPG-2 concentration. The alternative scenarios, based on the accident history or the plant's hazard analysis, are more likely to occur than the worst-case, reach an endpoint offsite, and for their definition active and passive safety measures can be taken into account. Information on the receptors of risk is also reported: The operator has to estimate residential populations within the circle of the worst-case and alternative release scenarios and to report whether areas of sensitive population (schools, hospitals, etc.) or great environmental interest are included in the circles. The results of worst-case and alternative scenarios, together with the information on the population distribution are reported in the RMP and are taken by the authorities as basis for the relevant case by case decisions, and especially for emergency planning.

various types of facilities. Each scenario is well determined: the conditions under which the accident occurs (release characteristics, meteorological conditions, etc.) and criteria concerning the maximum acceptable effects (thermal radiation, overpressure or toxic

Table 2
Reference scenarios and effect criteria used for land-use planning purposes in France (according to Ref. [32])

Scenario	Applicable to type of facility	Effects studied	Criteria corresponding to first deaths	Criteria corresponding to first irreversible effects
A: BLEVE (Boiling Liquid Expanding Vapour Explosion)	Liquefied combustible gases	Thermal radiation Overpressure	5 kW/m^2 140 mbar	3 kW/m^2 50 mbar
B: UVCE (Unconfined Vapour Cloud Explosion)	Liquefied combustible gases	Overpressure	140 mbar	50 mbar
C: Total instantaneous loss of containment	Vessels containing liquefied/non-liquefied toxic gases	Toxic dose	Based on LC 1%[a] and exposure time (passage of the cloud).	Based on IDLH[b] and exposure time (passage of the cloud).
D: Instantaneous rupture of the largest pipeline leading to the highest mass flow	Toxic gas installations when the containment is designed to resist external damage or internal reactions of products	Toxic dose	Based on LC 1%[a] and exposure time (duration of the leak).	Based on IDLH[b] and exposure time (duration of the leak).
E: Fire in the largest tank, Explosion of the gas phase for fixed roof tanks, Fireball and projection of burning product due to boilover	Large vessels containing flammable liquids	Thermal radiation Overpressure Missile and product projection originating from the explosions[c]	5 kW/m^2 140 mbar	3 kW/m^2 50 mbar
F: Explosion of the largest mass of explosive present or explosion due to a reaction	Storage or use of explosives	Thermal radiation Overpressure Missile and product projection originating from the explosions[c]	5 kW/m^2 140 mbar	3 kW/m^2 50 mbar

[a]Lethal Concentration to 1% of the population when exposed by inhalation for a specified time period.
[b]Immediately Dangerous to Life or Health. The concentration represents the maximum concentration of a substance in air from which healthy male workers can escape without loss of life or irreversible health effects under conditions of a maximum 30-min exposure time. The use of IDLH is presently under review.
[c]Modelling the behaviour of projectiles is a difficult task in general, however the phenomenon should be seriously taken into consideration especially for the siting of buildings, which are evacuated with difficulty.

dose) have been established. The description of these six scenarios [32], together with the maximum acceptable effects, is presented in Table 2.

The objective of the risk assessment procedure is the calculation of two distances:

- the distance at which the first death occurs (corresponding to probability of fatality 1%)
- the distance at which irreversible health effects occur.

For scenarios involving fire or explosion the affected area is considered to be circular and independent of the meteorological conditions. On the contrary, the effects of toxic substances do depend on the weather conditions. However, the variability in the wind-direction is not taken into account and the corresponding area is again considered as circular.

It should be noted that any conceivable scenario leading to consequences worse than those of the reference scenarios might also be used for the determination of the risk zones. However, scenarios with remote probability are not evaluated. In practice, the determination of the reference scenarios is a product of a co-operative procedure including compromises between the authorities and the plant-owner.

Land-use control is necessary for the area corresponding to the maximum calculated distance for all the scenarios evaluated. This area can in most cases be divided into two zones with different development restrictions. In the zone being closest to the installation, only 'housing and public building' developments not resulting in an increase in density are allowed. In the outer zone authorisation is given for developments with limited density, that is all categories of 'housing and public building' developments with the exception of high rise buildings and establishments receiving the public. Industrial installations can be permitted in these zones if certain minimum conditions are fulfilled. It is also worth mentioning that emergency plans are based on evaluation of more severe scenarios.

4.4. The risk based approach

4.4.1. General

A different philosophy is implied by the 'risk based' approach (also known as the 'probabilistic' approach). Various names have been used for characterising the risk assessment method implied by this approach, such as Probabilistic Risk Assessment (PRA), Probabilistic Safety Analysis (PSA), and Quantified Risk Assessment (QRA). The purpose here is not only to evaluate the severity of the potential accidents, but also to estimate the likelihood of their occurrence. In general, the methods use more sophisticated tools and in some way seem to be more complete in the analysis of risk than the methods previously described. However, they are more complicated, more time-consuming and more expensive. Criticism has also been expressed on the uncertainties associated, such as those related to the frequencies of occurrence assigned to some initiating events.

In general, the 'risk based' approaches define the risk as a combination of the consequences derived from the range of the possible accidents, and the likelihood of these accidents. Therefore, they usually consist of four phases:

- Identification of hazards,
- Estimation of the probability of occurrence of the potential accidents,

- Estimation of the consequences of the accidents, and
- Integration into overall risk indices.

Two measures of risk are usually calculated: (i) the *individual risk*, defined as the probability of fatality due to an accident in the installation for an individual being at a specific point, and (ii) the *societal risk*, defined for different groups of people, which is the probability of occurrence of any accident resulting at fatalities greater than or equal to a specific figure. Individual risk is usually presented by the isorisk curves, while F–N curves provide a visualisation of the societal risk. Another risk concept, *area risk*, is not actually a different measure of risk, but rather a combination of the risk imposed by several sources, and it is therefore expressed by individual and societal risk measures. Area risk is a very meaningful and useful concept, especially when a number of plants concerning a same area is considered [8,9].

From the methodological point of view, the use of these two criteria should be highlighted as one of the differences from the consequence based approach, in which the extent of consequences is used as the only criterion for LUP. For the calculation of individual and societal risks not only the evaluation of the consequences is necessary, but also the assessment of the probability under which the accidents are likely to occur. The individual risk criterion is applied for the protection of each individual against hazards involving the dangerous chemicals. This criterion does not depend on the population around the plant, or on the number of victims of the potential accidents. It expresses a pre-set level of risk, above which no individual is permitted to be exposed. With the individual risk criterion, the principle of *equity* in the distribution of risk is expressed.

The societal risk criterion is established for the protection of the society against the occurrence of 'large scale' accidents. For its calculation, not only the population density around the installation is taken into account, but also the population's temporal variation along the day, as well as the possibilities for emergency measures (distinction between indoors and outdoors). Usually the application of societal risk criterion is supplementary to the use of individual risk criterion. The underlying philosophy beyond its application is the fact that even when the individual risk criterion is met, if a population centre is located close to a 'safety distance' it is possible that a major accident will cause a large number of victims. With this criterion the *society's aversion against increased number of fatalities* is taken into account.

The general idea of establishing country-wide individual and societal risk criteria is given in Fig. 1. Usually there are three regions; an acceptable risk region, a non-acceptable risk one, and a region where the risk can be considered as affordable, however its reduction is strongly desired (ALARA principle—As Low As Reasonably Achievable).

The risk based approach has been adopted and is applied in the Netherlands, the UK and the Flemish region of Belgium. It is likely to be adopted in Denmark (although no explicit criteria have been established yet), whereas it has been proposed to be adopted in many other Member States of the European Union. Among the non-EU countries following the risk based approach are Australia and Switzerland. More specifically, in Australia [33] there are acceptability criteria for both individual fatality and injury risk. The individual fatality risk criterion is set at 10^{-6} fatalities per year for residential population and it increases or decreases accordingly in order to take sensitive population

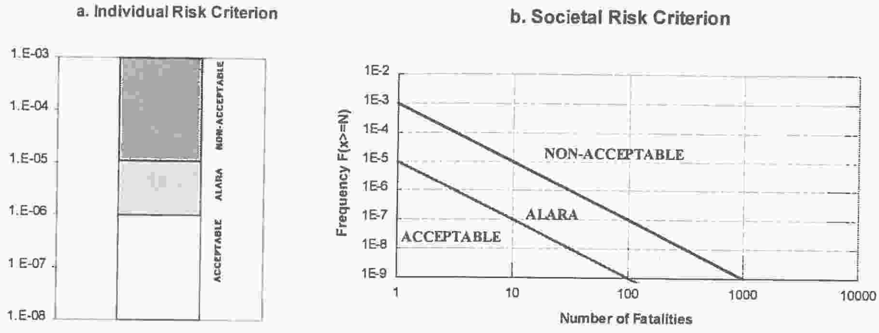

Fig. 1. Examples of Criteria for (a) Individual and (b) Societal Risk.

or industrial and sports areas into account (0.5×10^{-6} yr^{-1} for schools and hospitals, 5×10^{-6} yr^{-1} for sports areas and 50×10^{-6} yr^{-1} for industrial areas). The injury risk criterion states that certain threshold values of the physical effect causing injury (i.e., thermal radiation, overpressure, concentration of toxic substance) should not be exceeded in residential areas at frequencies greater than 50×10^{-6} yr^{-1}. These values are 4.7 kW/m^2 for thermal radiation, 7 kPa for explosion overpressure, and the concentration causing irritation to throat and eyes for toxic substances. Societal risk is taken into consideration, however no explicit criteria have been set so far.

In Switzerland [34–36] risk criteria are visualised by use of frequency–consequence (F–N) diagrams. Nine separate indicators are used to quantify the severity of the accident, namely, fatalities, injuries, evacuated persons, alarm factor, animals killed, area of destroyed ecosystem, contaminated area, polluted groundwater, and property losses. Obviously, these 9 indicators are not taken equally into account. There is a 'major accident index'—a kind of gravity scale—transforming the absolute number of consequence into a scale between 0 and 1, that expresses the severity of the accident. The frequency of exceeding certain levels of this index is then controlled through a diagram similar to the one depicted in Fig. 1(b). Low values of the major accident index are always acceptable, independent of their frequency. [6]

4.4.2. Example of use: Netherlands

In the Netherlands the External Safety Report (ESR), provided by the plant-owner, requires the quantification of risk, including the assessment of probability of occurrence

[6] It is worthwhile to refer to discussions in Russia, which take into account the local economic context. The proposal depicted in Ref. [37] takes into consideration the present situation of the industry in the country, the frequencies of industrial accidents and the actual situation of the technological equipment. Both individual and societal risk criteria are offered. Individual risk criterion considers risk of fatality of 10^{-4} yr^{-1} or higher as non-acceptable, while acceptable is considered a risk of 10^{-5} (for existing establishments) or 10^{-6} (for new establishments), or lower. The zone between 10^{-4} and 10^{-5} or 10^{-6}—for existing or new establishments, respectively—is a strict control zone, where the limitation to the population density is to be posed. Concerning societal risk, the authors assume 25 or more fatalities with frequency higher than 10^{-4} yr^{-1} as non-acceptable risk.

for the various accidents. Consensus has been achieved not only on the content of ESR, but also on the type of risk assessment to be performed. Thus, a complete Quantitative Risk Assessment (QRA) is required. The measures of risk provided are individual risk contours and societal risk (F–N) curves. It is also worth mentioning that consensus has been achieved between the industries and the public authorities in the method to be followed. Therefore nation-wide the SAFETI [38] method (although not always the SAFETI program) is used.

The risk criterion for the maximum individual risk of death in cases of existing major hazard sites is set at 10^{-5} per year [39–43]. This means that no housing is allowed in an area where the risk exceeds this value. This area can for instance be used for agricultural purposes. For siting of new major hazard installations, the criterion for individual risk should refer to the risk of death in everyday life, considered to be 10^{-4} for young and healthy people. The maximum acceptable mortality risk from all industrial sources to which one can be involuntarily exposed is thus defined to be 10^{-5}, that is an order of magnitude less.

For one single risk source, a maximum tolerable individual risk of death of 10^{-6} per year has been adopted that is, an increase of the risk of death by one percent. The risk contours corresponding to an individual risk of death of 10^{-6} per year thus define the outer border of safety zones around the proposed site. It should however be possible to accept higher risks in certain regions (e.g. villages where housing is along the one and only village road in an otherwise uninhabited area). For societal risk, the criterion adopted is $10^{-3}/N^2$, N being the number of fatalities, for existing as well as for new major hazard sites, but planning authorities may accept a higher value if there are proper motives to do that (land-use, financial aspects, employment, etc.). The earlier use of levels of negligible risk has been abandoned since this criterion led to misunderstandings concerning risk management, and only the maximum tolerable risk is now used as a criterion. When the risk is below the maximum tolerable risk level, still an ALARA (As Low As Reasonably Achievable) approach to reduce the risk has to be applied. The past and present risk tolerability criteria are summarised in Table 3.

When old installations have to be replaced by new ones, the tolerability criteria for existing sites apply. For an establishment that needs to expand, a 'standstill' criterion is used, that is, an increase of the risk is not accepted.

It should be mentioned that the risk based approach has been used and relevant criteria have been adopted for the evaluation and control of *transportation* risk. Setting tolerability criteria for risks to *surface water* with respect to major hazards is another

Table 3
Past and present Dutch risk tolerability criteria (according to Ref. [39])

	Individual risk criteria		Societal risk criteria	
	Present	Previous	Present	Previous
Existing installations	10^{-5} per year	10^{-5} per year	$10^{-3}/N^2$	$10^{-1}/N^2$
New installations	10^{-6} per year	10^{-6} per year	$10^{-3}/N^2$	$10^{-3}/N^2$
Negligible risk	Always ALARA applied	10^{-8} per year	Always ALARA applied	$10^{-5}/N^2$

field where a lot of effort is being made. However, no criteria will be stated before international consensus on the matter has been reached. The risk assessment is so far mainly used for setting priorities for further environmental improvements at a site, and also to set priorities between sites.

4.4.3. Example of use: The UK

The methods followed for risk assessment in the UK are well-structured similarly to the Dutch procedures, providing however, relatively more flexibility to planning authorities. The bodies involved in the decision-making process are two: The local planning authorities and the competent authority for the implementation of the Seveso Directive, the Health and Safety Executive (HSE). The latter has an advisory role on issues of major accident hazards.

The Health and Safety Executive has from the late 80s elaborated explicit methods and criteria for giving its advice [44–50]. For advising on toxic substance releases, the 'risk based' approach (Quantified Risk Assessment—QRA) is applied, whereas advice on thermal and explosion hazards is based mainly on the estimated consequences ('consequence based'). The reason for this differentiation is the fact that the consequence vs. distance curve for thermal or explosion hazards exhibits a sharp decline at a specific distance, where specific thermal radiation or overpressure levels are achieved. The curve can therefore be approximated by a 'step' function:

Risk $= 1$ for distance $< d_0$, and

Risk $= 0$ for distance $\geq d_0$

It is therefore possible to avoid assessing the frequencies of occurrence of the selected scenarios and focus the analysis only on the assessment of the consequences (since consideration of the scenarios' frequencies will only multiply the above 'step-function' by the relevant frequency). However, when synthesis of the risks from various sources is required, a complete QRA is performed.

For toxic substances, zoning follows the risk contours based on the probability of receiving at least a 'dangerous dose'. The latter is determined as the dose, which causes severe distress to almost everyone, a substantial fraction would need medical attention, some would be seriously injured requiring prolonged treatment and the highly susceptible might be killed. As discussed by Pape [48], this definition of individual risk allows for taking some injury effects into account as well as death and expresses some conservatism to take into consideration the uncertainties connected with the probit function, however it is rather arbitrary requiring some judgement in the definition of 'dangerous dose'. It should also be noted that the criterion for determining the outer zone is set equal to 1/3 of the criterion for the middle zone in order to take into consideration the high vulnerability of specific population groups (elderly, children).

Within the consultation zone, sub-zones are identified, as in Table 4. The three sub-zones within the consultation zone are defined as follows.

- The *inner zone* is defined by an individual risk exceeding 10 in a million per year (10^{-5}) of receiving a 'dangerous dose' or worse. This means that for the more vulnerable members of the population the risk of death at the zone border is about 10 in a million per year. This figure is compared to the risk of being killed in a road accident, which has been calculated to be 100 in a million per year.

Table 4
Criteria used for the definition of zones around an installation in UK (according to Ref. [44])

	Inner zone	Middle zone	Outer zone
Risk based criteria	10^{-5} per year	10^{-6} per year	3×10^{-7} per year
Consequence based criteria	Fireball radius	1000 TDU[a]	500 TDU[a]
	600 mbar	140 mbar	70 mbar

[a]Thermal Dose Units, combination of thermal flux and duration of exposure (dimension $(kW\ m^{-2})^{4/3}$ s).

· The *middle zone* is defined by an individual risk exceeding 1 in a million per year (10^{-6}) of receiving a ‘dangerous dose’ or worse. Thus, at the outer border of the middle zone, the risk of death for the more vulnerable people is about 1 in a million per year. Assessments performed by the HSE suggest that for the majority of population this risk corresponds to a risk of death of about 1/3 in a million per year. This figure is compared to the risk of being killed by lightning, which has been calculated to be 0.1 in a million per year.

· The *outer zone* is defined by an individual risk exceeding 0.3 in a million per year (3×10^{-7}) of receiving a ‘dangerous dose’ or worse. This criterion is appropriate for highly vulnerable or very large public facilities.

For consequence based zoning in the case of LPG storage, the sub-zones are defined as follows: The inner zone corresponds to the fireball radius or explosion overpressure of 600 mbar, the middle zone represents 1000 Thermal Dose Units (TDU—dimension $(kW\ m^{-2})^{4/3}$ s) or explosion overpressure of 140 mbar, and the outer zone 500 thermal dose units or explosion overpressure of 70 mbar. Especially concerning the explosion

Table 5
The HSE siting policy within the consultation zones (according to Ref. [44])

Category of development	Inner zone Individual risk exceeds 10^{-5}	Middle zone Individual risk exceeds 10^{-6}	Outer zone Individual risk exceeds 0.3×10^{-6}
Highly vulnerable or very large public facilities (schools, hospitals, old person's accommodation, sports stadium)	Advice against development	Specific assessment necessary (advice against if > 25 people)	Specific assessment necessary
Residential (housing, hotel, holiday accomodation)	Advice against development (> 25 people)	Specific assessment necessary (advice against if > 75 people)	Allow development
Public attractions (substantial retail, community and leisure facilities)	Specific assessment necessary (advice against if > 100 people)	Specific assessment necessary (advice against if > 300 people)	Allow development
Low-density (small factories, open playing fields)	Allow development	Allow development	Allow development

hazards, the 600 mbar criterion stands for causing total demolition of the buildings (high probability of death of the occupants), whereas 140 mbar causes some structural damages which may lead to some fatalities, and 70 mbar stands as a threshold under which structural damages are unlikely to occur and no fatalities are expected (although some windows may be broken).

Within these sub-zones, advice on proposed developments belonging to the four categories is given according to Table 5.

For the siting of new installations posing major hazards, the HSE applies similar assessment methods but not necessarily the strict inverse of the criteria defined for the development in the vicinity of an existing major hazard site. The decision matrix shown in Table 5 is however used and judgements are also based on population density within the risk contours. At present, no criteria for siting of new major hazards have been adopted. Moreover, concerning the siting of establishments where explosives are manufactured, stored or handled, different procedures apply. For these cases the HSE controls the siting by licensing under the Explosives Act 1875. Different arrangements also apply for siting of pipelines containing hazardous substances.

5. Application of the various approaches: Illustrative examples

In the following, the application of the various approaches in simple cases will be discussed. This discussion will serve more as an illustrative example to clarify the concepts, rather than as a well-analysed case study for the comparison of the methodologies.

5.1. Example 1

The case study is borrowed from the literature [32] and it concerns a chlorine facility. A reference scenario used for the identification of risk assumes the guillotine rupture of the largest branch connection and the release of liquefied chlorine. The release is assumed to be under control after 3 min.

In order to discuss similarities and differences one has to establish a common base. The assumption made here considers that the reference scenario applied for the 'consequence based' approach is also included in the set of scenarios examined for the 'risk based' approach, and that the same models are used to evaluate the consequences. According to Ref. [32], the data and the recommended calculations are as follows:

- Diameter of the branch: 40 mm
- Temperature of chlorine: 25°C
- Pressure: 7.6 bar
- Height of liquid above the orifice: 2 m

The consequence assessment consists in calculating the release rate of chlorine, modelling its dispersion under unfavourable weather conditions and, according to the 'consequence based' approach, calculating the distances at which the concentration's value reaches the levels corresponding to lethal effects and to irreversible health effects. Since the purpose of this discussion is to highlight similarities and differences between the approaches, and since the results of the consequence assessment do not affect this discussion, no attempt was made to verify them, but they are simply taken directly from Ref. [32] and they are just quoted here.

The recommended approach first calculates the release rate in the liquid phase, then the fraction of liquid evaporated immediately by flash is calculated, the generation of aerosols is taken into account, and a dispersion model is applied. Very unfavourable weather conditions are assumed, that is D and F stability classes and 3 m/s wind speed. Finally, in order to calculate the distances corresponding to doses that cause deaths and irreversible effects to the population, the toxicity of the hazardous substance is taken into account. Duration of inhalation is assumed to be 3 min.

5.1.1. Safety distances according to the consequence based approach

Dose thresholds	Dose	Distance
Dose corresponding to the start of lethal effects (corresponding to 1% conditional probability of fatality)	360 ppm for 3 min	1380 m
Dose corresponding to the start of irreversible effects	65 ppm for 3 min	3940 m

5.1.2. 'Generic' safety distances

According to this approach, the safety distance would have been taken directly from a relevant list. This facility is included in the category 'inorganic chemical industry', and a unique distance is recommended in the list for all similar facilities. It is worth noting that there is no difference if the substance is Cl_2, or H_2SO_4, or HF. The quantity and the conditions of the chemical do not affect the recommended distance, too. This distance, in the case of the tables used in Ref. [29] for example, would be 1000 m.

5.1.3. Safety distances according to the risk based approach

According to the risk based approach, a number of possible accident scenarios should be analysed. For each scenario, both the consequences and the frequency of occurrence should be assessed. For comparison reasons, let's assume that the scenario analysed above is the worst scenario, it is included in both the analyses, and the same models are used for its evaluation. The final risk at distance 1380 m calculated by the risk based approach would be:

$$R = \sum_{i=1}^{N} p_i c_i = \sum_{j=1}^{N-1} p_j c_j + p_w c_w = A + p_w(10^{-2})$$

where R is the total risk, i, j are indices on the assessed accident scenarios ($i = 1, \ldots, N$) ($j = 1, \ldots, N-1$), w is an index for the worst accident, p_i is the frequency of occurrence of scenario i, c_i is the probability of fatality conditional on the occurrence of scenario i.

The above relation expresses the fact that the risk depends not only on the worst (or reference) scenario, but also on the whole range of potential accidents. Moreover, it depends heavily on the corresponding frequency p_i.

In comparing the two approaches, one should investigate whether the above expression, giving the risk as it is calculated by the risk based approach, is higher or lower than the 10^{-6} level usually set as a tolerability level. If this risk is lower, then the 10^{-6} level will be closer to the installation, and, therefore, the risk based approach will give shorter distances. Usually, the frequency of the most severe scenario (p_w) is very low (high consequence—low probability scenarios). If, in addition, the consequences of the rest scenarios were not significant, then the total risk, calculated by the risk based method at the distance of 1380 m, would be lower than the tolerability level of 10^{-6}. On the contrary, if p_w is about 10^{-4}, or if the sum A exceeds 10^{-6}, then the total risk will also exceed the tolerability level of 10^{-6}, and the distance calculated by the risk based approach will be greater than the one calculated by the consequence based approach. Similarly, there are many cases in which the distances provided by the two approaches are similar.

5.2. Example 2

The purpose of the second example is to discuss and give insights to the applicability of the methods described above, by applying them all to a reference installation and comparing the results. In order to facilitate this discussion, a reference installation from a European benchmark exercise has been used. The Benchmark Exercise on Major Hazards Analysis (BEMHA) [51,52] was carried out during the period 1988–1990 under the co-ordination of the Joint Research Centre (JRC), under partial funding of the European Commission, and with the participation of 11 teams from all over Europe, representing research institutes, engineering companies, control authorities, and industries involved with risk analysis. This exercise aimed on one hand at assessing the state of the art of chemical risk analysis, identifying and understanding the available methods and their strengths and weaknesses, and on the other hand at analysing the uncertainties involved, their origins and their impact on the results. An ammonia storage facility served as the reference plant, and it was completely analysed with respect to the risks involved by all 11 teams independently. The results of this analysis were compared together with the methodologies, data and models employed. This comparison served as a basis for the design of the second phase of the project, in which a set of selected partial exercises with predefined boundary conditions was performed in an attempt to identify the sources of the overall spread in the results. The benefits and insights gained from this exercise have many times been acknowledged and have proven to be useful not only for the scientific community as a whole, but also for the participating institutions [53,54].

The reference plant [52], which will also serve as a reference for the discussions herein, is an ammonia storage plant and is schematically depicted in Fig. 2. It consists of an ammonia sea terminal, an undersea pipeline connecting the sea terminal with a refrigerated storage tank, a 15 000 tonnes refrigerated storage tank, an underground pipeline connecting the refrigerated tank with two pressurised vessels within a fertiliser plant, and two pressurised vessels. Liquefied ammonia at −33°C arrives by ship at the sea terminal and it is unloaded to the cryogenic storage tank (unloading capacity 600 t/h). From this tank, ammonia is pumped to the pressurised storage vessels, located

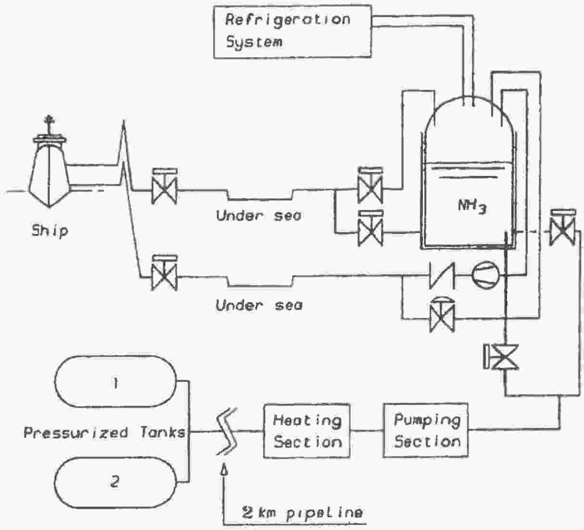

Fig. 2. Simplified diagram of the reference plant for illustrative example 2.

2 km away, where it is stored under ~ 13 bar pressure and at 20°C temperature. Their normal inventory is 60 t, operating under 50% capacity.

A number of accident scenarios were identified and assessed both in terms of their frequency of occurrence and of the relevant consequences. Among these, the ones most contributing to the overall risk *at long distances from the source* are the most interesting from the land use planning point of view. Since the purpose of the discussion here is not to repeat the relevant calculations, but rather to investigate their impact to LUP, and in order to simplify the risk assessment procedure, only the following representative scenarios are considered, which most contribute to the level of risk at long distances from the source:

1. Rupture of the roof of the cryogenic storage tank due to overpressure, with a frequency of 2×10^{-4} per year;
2. Guillotine break of the pipeline between the sea terminal and the cryogenic storage tank, at a point near the tank (above ground), with a frequency of 10^{-4} per year;
3. Catastrophic rupture of a pressurised vessel, with a frequency of 5×10^{-5} per year.

It is assumed that the above scenarios form the set of reference scenarios under concern according to the consequence based approach (among which the worst will be identified), while at the same time they constitute the main contributors of risk at long distances from the source in applying the risk based approach. Concerning the above frequencies it should be noted that the selected values are not the result of any specific analysis but they have been selected to be within the range of values provided by the BEMHA participants (usually the mean value has been chosen). The selected values are therefore reasonable frequencies, representative of the respective accident scenarios. As far as the weather conditions are concerned, the application of the consequence based approach assumes the worst between the classes D2, F2 and D5 (weather stability class D or F and wind velocity 2 m/s or 5 m/s), while the application of the risk based method takes the complete variability in stability class, wind speed and wind direction into account (see description of weather conditions in BEMHA project in [51]).

For assessing the consequences of the selected accident scenarios the methodology and associated computer tools SOCRATES (*S*afety *O*ptimisation *C*riteria and *R*isk *A*ssessment *T*ools for *E*mergencies and *S*iting) [55] have been used. The results of consequence assessment are summarised in the following table:

	Accident Scenario	Distance for the 'first death'		
		D2	F2	D5
1	Rupture of the roof of the cryogenic storage tank due to overpressure	800 m	1280 m	Very short
2	Guillotine break of the pipeline between the sea terminal and the cryogenic storage tank, at a point near the tank (above ground)	1180 m	1850 m	Very short
3	Catastrophic rupture of a pressurised vessel	980 m	1520 m	Very short

The circles corresponding to the D2 and F2 distances together with the isorisk contours corresponding to 10^{-5}, 10^{-6} and 10^{-7} risk levels are presented in Fig. 3. It is clear that a 'strict' application of the consequence based approach results in establishing

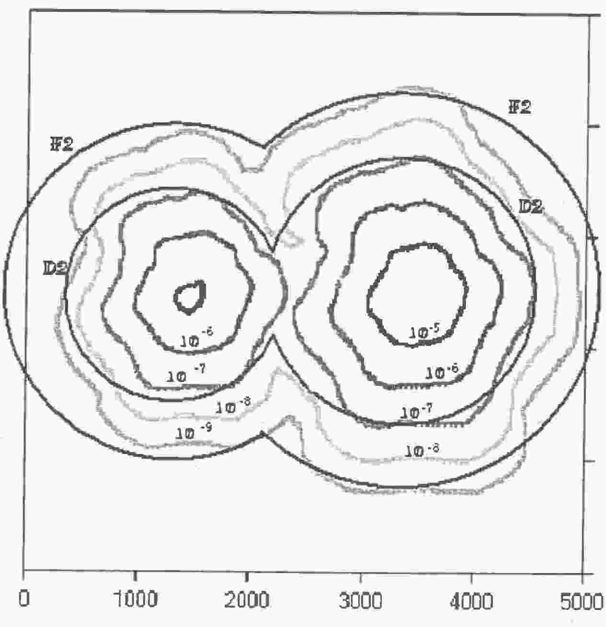

Fig. 3. Results of consequence based and risk based approaches for example 2.

a control zone of 1850 m from the refrigerated storage tank and 1520 m from the pressurised tank area, while application of the risk based approach with a 10^{-6} risk criterion results in the corresponding zone, as shown in Fig. 3. There is a significant difference between the zones calculated by the two approaches. If generic distances are also under consideration, tables from Ref. [29] give 1000 m (inorganic chemistry), whereas an ILO (International Labour Organisation) document [56] also recommends a 1000 m distance for ammonia storage.

It is thus clear that a 'strict' application of the various approaches can give incomparable separation distances. Let's assume, however, that the planning authorities handling the case are in front of conflicting objectives and interests (e.g., development plans of a local community), which they are trying to satisfy, and they consider the F2 zone as extremely extended. Taking into consideration the fact that in the specific case the D stability class is the most frequent (71%) and that the consequence based approach considers D class as relatively bad (close to the worst), a regional planner may consider that *adequate protection* is provided if the D2 zone (1180 m from the refrigerated tank and 980 m from the pressurised tank) is chosen instead. In a similar way, a regional planner applying the risk based approach may feel a bit uncertain about the frequencies selected and may wish to increase the *protection* provided to the population by extending the relevant zone to the 10^{-7} risk contour. This contour is practically equal to the D2 zone, provided by the consequence based approach. It is therefore an interesting conclusion that, although great differences are reported from a 'strict' and 'mathematical' application of the two approaches, their realistic application—which is the everyday practice—may under certain circumstances result in comparable distances and zones. This result, which seems surprising from a first point of view, has also been reported in a study on the approaches followed in the UK and France [57]. It was found that in the majority of the cases examined (about 60%) the adopted distances were comparable.

To take into consideration the multiple social and other factors, which are involved, has been widely recognised. Cost-effectiveness and multiobjective techniques have been proposed for taking these factors into account [58], whereas a research project partially funded by the European Commission (LUPACS project, in the framework of the Environment and Climate Programme of DG XII, with the participation of 4 research institutions, 2 central and 3 regional/local authorities) attempts to address the problem from a similar viewpoint.

Another issue related to the land use planning problem is the accuracy of results of Risk Analysis and the associated uncertainties. Fig. 4 presents the results provided by the BEMHA participants in analysing a pre-defined case with agreed boundary conditions and a common vulnerability model (phase II of the project, as mentioned above). The variation in the results is due to the different models employed and due to assumptions/expert judgement in applying the models and setting the relevant parameters. The distance corresponding to the 10^{-3} conditional risk level (individual risk conditional to the fact that the respective accident scenario has been realised) varies from 500 m to 1800 m. This means that if the 10^{-6} individual risk criterion has been adopted, and if the overall frequency from all scenarios is assumed to be 10^{-3} per year —the described scenario being a representative one, the LUP zone assessed by the different teams would also vary from 500 m to 1800 m. These considerations reveal the

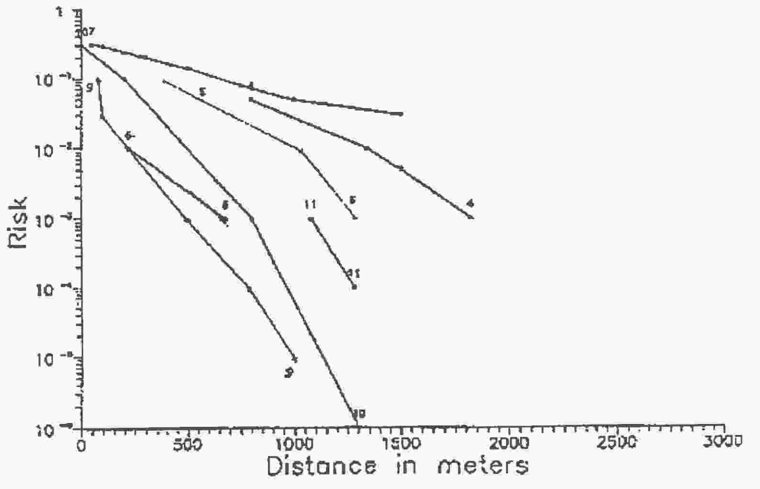

Fig. 4. Risk vs. distance for a common case analysed in BEMHA.

importance of achieving a consensus and of identifying and understanding the uncertainties associated with the Risk Assessment procedure. In this context and in order to gain insights in the origin of the uncertainties, a new benchmark exercise under the project title ASSURANCE (*ASS*essment of *U*ncertainties in *R*isk *AN*alysis of *C*hemical *E*stablishments) has been initiated with the participation of European research institutes and consulting companies and with partial funding from the Commission.

6. Conclusions

In this paper the approaches followed in support to land-use planning decisions concerning industries handling hazardous materials were reviewed. The analysis focused on the European continent, however, information on the practice in other countries world-wide was also given. Although the three categories of approaches identified, namely the ''generic distances based on historical reasons and the environmental impact of the industrial activities'', the 'consequence based' and the 'risk based' approaches, are completely different, a preliminary analysis of their applicability through illustrative examples proved that in certain cases it is possible that the resulting protection zones are not very largely different.

It should be noted that solely a comparison of the numerical land-use planning criteria used in different countries is not sufficient: the methods and hypotheses used in the stage of risk analysis can also generate substantial differences. This issue needs to be further considered and new insights should be gained by the ASSURANCE project now starting, indeed since the land use planning necessarily includes public consultation it is indispensable that the risk assessment procedure be transparent together with its assumptions and implied uncertainties. A discussion of the general implications of public risk perception and participation was outside the scope of this paper, and for the relevant information the reader can refer to another paper in this journal (see also Ref. [59]).

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