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A global view on ARAMIS, a risk assessment methodology for industries in the framework of the SEVESO II directive

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Abstract

The ARAMIS methodology was developed in an European project co-funded in the fifth Framework Programme of the European Commission with the objective to answer the specific requirements of the SEVESO II directive. It offers an alternative to purely deterministic and probabilistic approaches to risk assessment of process plants. It also answers the needs of the various stakeholders interested by the results of the risk assessment for land use or emergency planning, enforcement or, more generally, public decision-making. The methodology is divided into the following major steps: identification of major accident hazards (MIMAH), identification of the safety barriers and assessment of their performances, evaluation of safety management efficiency to barrier reliability, identification of reference accident scenarios (MIRAS), assessment and mapping of the risk severity of reference scenarios and of the vulnerability of the plant surroundings. The methodology was tested during five case studies, which provided useful information about the applicability of the method and, by identifying the most sensitive parts of it opened way to new research activity for an improved industrial safety.

Keywords: Risk analysis; Process industry; SEVESO II directive; Safety barriers

1. Introduction

In the beginning of this new century, some technological accidents like Enschede (2000), Toulouse (2001) or Lagos (2002) have led the public to wonder or even mistrust both the industry and the regulatory authorities in their risk-informed decisions. The communities want now to be informed and require more transparent decision-making processes. Risk-based decisions of course require some reliable scientific input from risk analyses. But from one risk analyst to the next, noteworthy variation exists in the results, which would affect any relevant local decision. That is why emerged the need for a methodology giving consistent rules to select accident scenarios and taking into account safety management effectiveness for risk control demonstration. In the context of Seveso II directive [1], there is also an underlying need for a method that could reach a consensus amongst risk experts throughout Europe.

ARAMIS overall objective was to build up a new accidental risk assessment methodology for industries that combines the strengths of both deterministic and risk-based approaches [2]. Co-funded under the fifth EC Framework Programme, this 3-year project started in January 2002 and finished at the end of year 2004. One year later, the methodology is achieved and aims at becoming a supportive tool to speed up the harmonised implementation of SEVESO II Directive in Europe. This paper intends to summarise the major features of the methodology and to show how the needs of ARAMIS potential users were addressed. In a second part, the feedback from the case studies realised during the last year of the project will be discussed. These were carried out on industrial plants, in countries with a consequence-based approach (France and Denmark) and a risk-based approach (Netherlands). The full test of the method in two new Member States (Slovenia and Czech Republic) has enabled to validate the method and has

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also contributed to the dissemination process towards these countries.

2. Needs of potential ARAMIS users

The potential stakeholders interested by the results of ARAMIS are numerous but the most concerned are the plant operators, the competent authorities and the local authorities. If all of them have an interest in the same risk management process defined by the SEVESO II directive [1], their needs are slightly different. The plant operator needs a method to identify, assess and reduce the risk. This method has to be accepted by the competent authorities. This method also has to bring useful information about the ways to reduce the risk and to manage it daily. The competent authorities need to be able to assess the safety level of the plant, particularly through the safety report. They need to know why scenarios have been selected for modelling of consequences. Both need to assess the influence of the safety management on the safety level: on one hand, the plant operator has to be able to improve the plant management to reduce the risk and, on the other hand, the competent authority has to assess a true risk level which takes into account this major influencing factor. Indeed, about 80% of the major accidents have causes related with human and organisational factor, which is a sufficient reason to take these aspects specifically into account.

The local authorities are interested in land use planning issues. They need to have a clear report about the risks or hazards their population actually faces. They also want to get information that can be used as a decision-aiding tool to define priorities or choose among alternatives. Basically, their capacity is about reducing vulnerability either by limiting the number of targets exposed to the risk or by introducing obstacles between the source and these targets. They also need to trust the plant operators and competent authorities when they propose risk or consequence-based contours from scenarios.

The aim of ARAMIS was to answer these needs [3]. It was also to bridge the gaps and build the convergence between the deterministic approach and the probabilistic approach and to resolve some difficulties inherent to each of them. These limitations have been discussed by Christian Kirchsteiger [4]. As far as the deterministic approach is concerned, the limit deals with the difficulty to justify the choices of the reference scenarios used for land-use planning decisions. Most of the time the selection is not about worst-case scenarios but an implicit choice is made to eliminate those, which seem too improbable. For the probabilistic approach, the difficulty resides both in producing the probability data and in interpreting the results to take appropriate decisions. ARAMIS does not completely solve these difficulties but provides the tools and the structure to improve decision-making. It also provides a framework for the definition of further research programs toward an integrated approach as discussed in the last paragraph.

3. Lessons learnt from previous projects

The ARAMIS methodology builds further on methods studied in the fourth Framework Programme mainly the ASSURANCE project, further described in details hereunder, and the I-RISK project which provides a methodology for in-depth judgement of safety management requirements for the design, operation and maintenance of major hazards plants [5].

ASSURANCE [6] means ASSessment of Uncertainties in Risk Analysis of Chemical Establishments. This project, which started in 1998 and ended up in 2001, was a benchmark exercise on risk analysis of chemical installations to understand discrepancies between experts.

The project consisted in the comparison of the selection of scenarios, the comparison of the estimation of the consequences and finally the comparison of the estimation of the probabilities.

The partners used various risk analysis techniques and arrived at quite different conclusions with respect to the selection of the scenarios, the estimation of their probabilities and the estimation of their consequences. For example, in terms of probabilities, for a classical event which is the "Rupture of 4 in. pipe of ammonia on a distribution line", the most optimistic partner estimated a probability of occurrence at 3.4×10^{-8}/year, and the most pessimistic partner at 2.3×10^{-4}/year.

Concerning the consequences of the scenario, for a rupture in a pressurised tank, the distance to reach the end point 6200 ppm in a normal atmospheric condition, was estimated by the most optimistic partner at 0.4 km and by the most pessimistic partner at 2 km. The last comparison concerned the iso-curves for 10^{-5}/year that a person die in the vicinity of the plant because of an accident. There is a difference of about 800 m about the most optimistic and the most pessimistic partners.

The ASSURANCE project has shown that there were discrepancies between the experts in the definition of scenarios considered for risk assessment. Some assumptions were different and this had a strong impact on consequence calculations. There were also discrepancies in the estimation of the probabilities of some events because there is a lack of reliable and contextual data (on failure rates, reliability...). Moreover, the project pointed out that risk curves mapping is not meaningful for local authorities and the public (consequence-based approach countries)

4. ARAMIS: a methodology based on a series of concepts and tools

ARAMIS is based on a definition of *risk*, which defines the elements on which the risk analysis should concentrate [7]. The risk is the probability that an element of the territory suffers a damage. The probability can also be expressed in terms of frequency. To observe a damage, a dangerous phenomenon with a given intensity has to hit a vulnerable element. The level of expected damage is determined by the *vulnerability* of the element and the *intensity* of the phenomenon. In ARAMIS, the combination of *frequency and intensity* has been called the *severity*. The method aims at assessing separately the severity and the vulnerability to provide to decision makers elements to assess the resulting risk

$$\text{frequency} \times \text{intensity} = \text{severity},$$

$$\text{intensity} \times \text{vulnerability} = \text{damages},$$

$$\text{risk} = \text{frequency} \times \text{intensity} \times \text{vulnerability}$$

The assumption of ARAMIS is that the frequency or probability of an accidental event is determined by two components: the *frequency of the initiating events*, i.e. the causes of the accidental scenario, and the *reliability and efficiency of the safety barriers* that prevent the occurrence of this scenario. To assess the risk it is therefore indispensable to identify the potential causes of the accident and the safety barriers and quantify their contribution to the frequency of the critical event.

The efficiency and reliability of the safety barriers is in turn very much influenced by the quality of their *management*. If the barriers are properly designed, installed, used, maintained and improved, they should be efficient and fulfil their goal. All these aspects are addressed through the safety management system that has to be assessed to take its influence into account. But the safety management system can be efficient only if the employees have a clear understanding of how they can interact with the safety of the installation. This relates to *safety culture*. ARAMIS proposes tools to assess the safety culture and to link its quality with the performances of the management system.

As far as the intensity is concerned, the previous projects like ASSURANCE had shown that one of the critical steps of the risk assessment process was the choice of the *reference accident scenarios*, i.e. of the hypotheses considered for the modelling of the accidental scenarios. ARAMIS proposes solutions to improve this selection process, to identify among the large variety of scenarios that can result from the risk analysis those which have a significant contribution to the risk. This selection is made with the use of a *risk matrix*.

Once the reference accident scenarios are selected, the decision-making process involves the definition of risk in the surroundings of the plant by aggregating the contributions of all the studied scenarios. A common approach of the risk aggregation consists in defining the individual probability of fatality. This is what is done in the traditional QRA methodology. This approach however has the disadvantage to consider only one type of consequence, whereas the effect thresholds used in various countries also consider the irreversible and the reversible effects on human as well as the effects on buildings. ARAMIS proposes the definition of a risk *severity index* to aggregate the risk with various types of effects. This severity index can be calculated in each spot of the surrounding territory and drawn on a map.

Once the severity is known, the final assessment of the present risk is done by overlaying the severity maps with the vulnerability map of the surroundings. To assess the vulnerability, a *vulnerability index* has been developed. It is based on the assumption that, on a given portion of the territory, the level of damages is proportional to the number of vulnerable elements weighted by their relative vulnerability to the effects that can impact them. The vulnerability index is then a linear combination of the number of various types of potential targets.

Beside these concepts, ARAMIS provides a series of methods and tools to put them into application.

5. Main features of the ARAMIS methodology

ARAMIS is divided into the following major steps (Figs. 1 and 2):

- Identification of major accident hazards (MIMAH).
- Identification of the safety barriers and assessment of their performances.
- Evaluation of safety management efficiency to barrier reliability.
- Identification of reference accident scenarios (MIRAS).
- Assessment and mapping of the risk severity of reference scenarios.
- Evaluation and mapping of the vulnerability of the plant's surroundings.

5.1. Identification of the major accident hazards (MIMAH)

MIMAH [8,9] is the method for the identification of major accident hazards. It is based mainly on the use of bow tie diagrams (Fig. 3), composed of a fault tree and an event tree. The major input of ARAMIS was to define a precise bow tie structure and to define precisely and exhaustively the list of equipment, potential critical events and their consequences. The critical events were defined to be either losses of containment for fluids or losses of physical integrity for solids. The complete list contains 12 critical events including breach, collapse, explosion, etc.

From a description of the plant including the chemical substances used, produced or stored, it is possible from MIMAH to list all critical events susceptible to occur in the plant. Then, for each of these critical events, MIMAH allows to identify all their consequences in terms of secondary events and dangerous phenomena.

Then, MIMAH provides the user with a set of generic fault trees, which are based on the most frequently observed causes [10]. From these generic fault trees, the user can

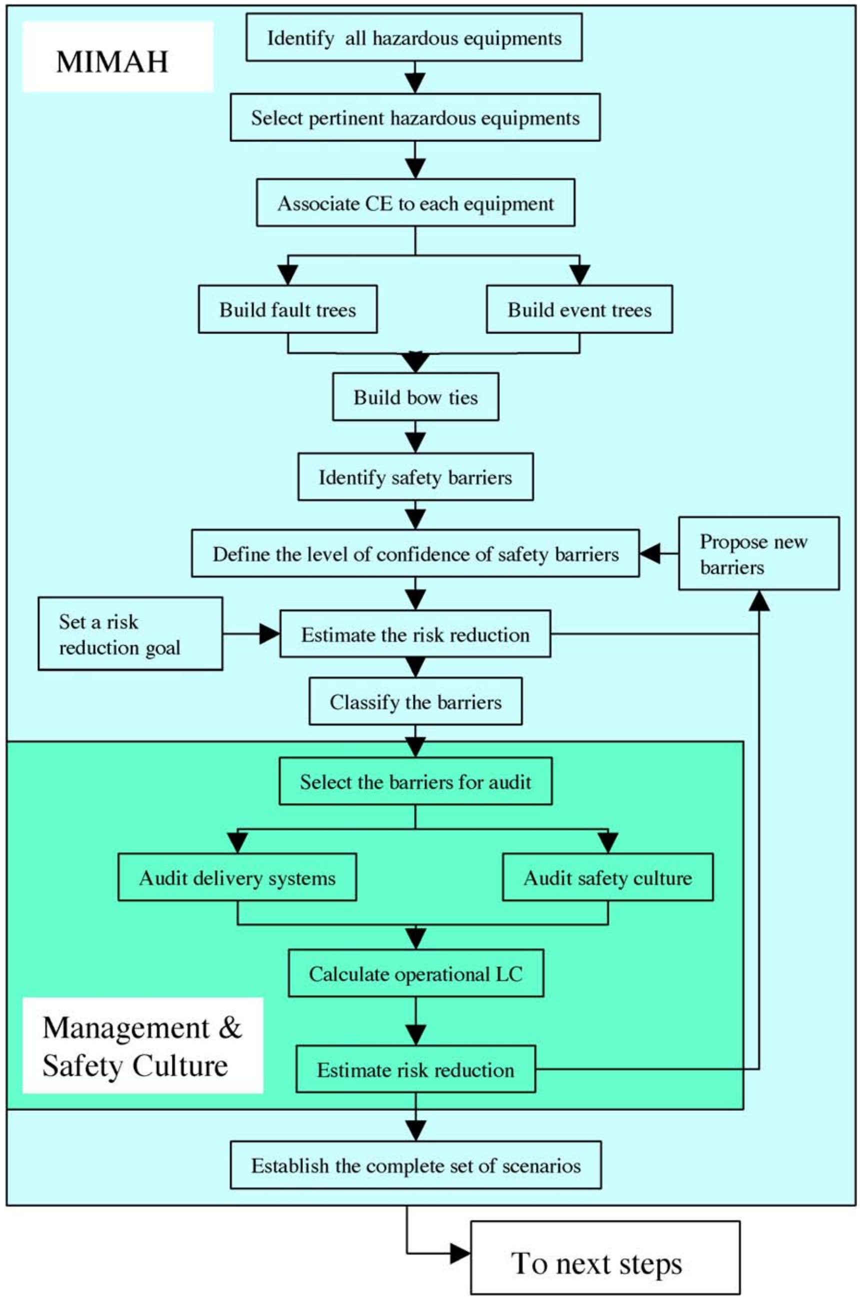

Fig. 1. First steps of the ARAMIS methodology.

build specific fault trees that take into account the specificity of the plant: types of process used, presence of equipment, etc. The specific fault trees are obtained mainly by the suppression of causes and consequences, which are not relevant to the context without any consideration on probability at this stage. It is important to notice that both the fault and event trees are considered without safety barriers, which will be defined in the next step of the method. This has the advantage to make an explicit distinction between hazard and risk. This first step allows the identification of hazards. The next one aims at identifying the risks, which result from the hazard scenarios and the failure of safety barriers.

5.2. *An alternative to classical probabilistic approaches*

Standard risk analysis methods propose to assess the probability of major accident and to decide from this evaluation whether the risk is acceptable or not. But, during the ARAMIS project, this calculation of the probability was shown not to be an easy task. An inventory of the probabilistic data sources was carried out. It turned out that

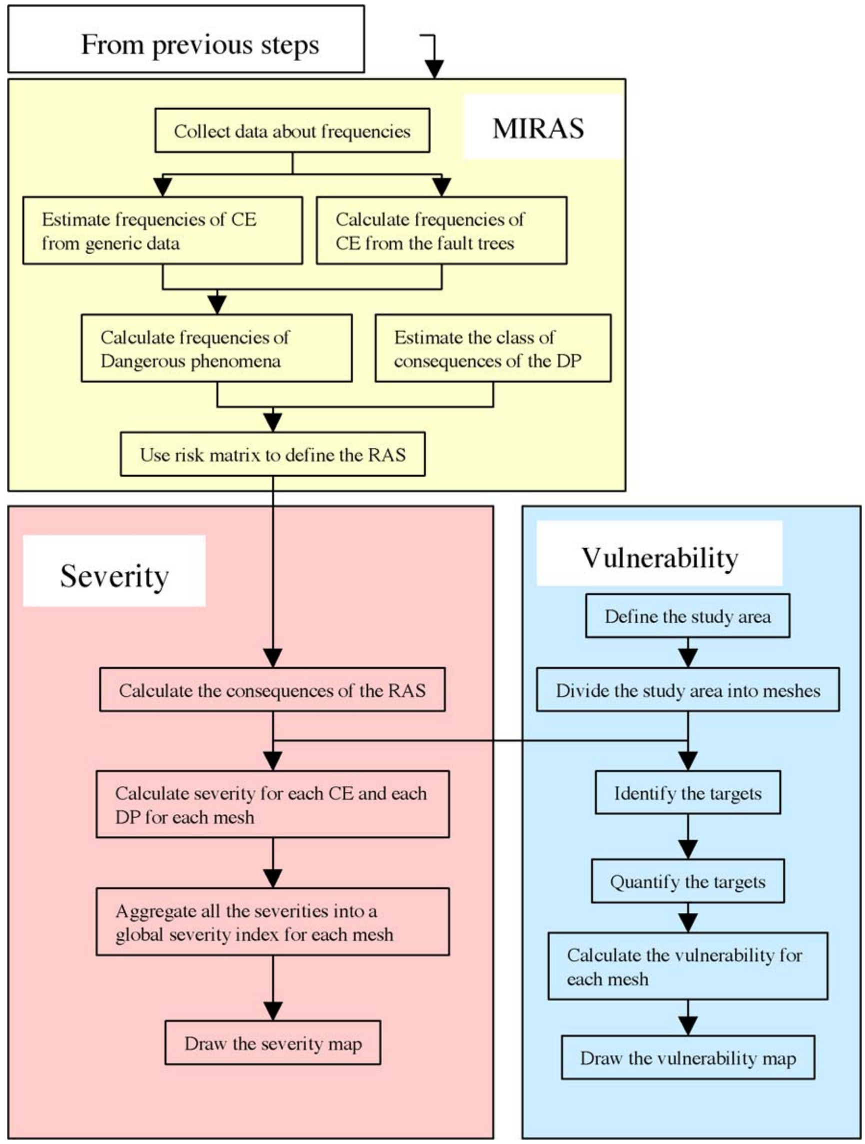

Fig. 2. Last steps of the ARAMIS methodology.

many of the available data are not adapted for use with the tools developed in the first steps of the methodology. Others were obtained by statistical methods in limited geo-

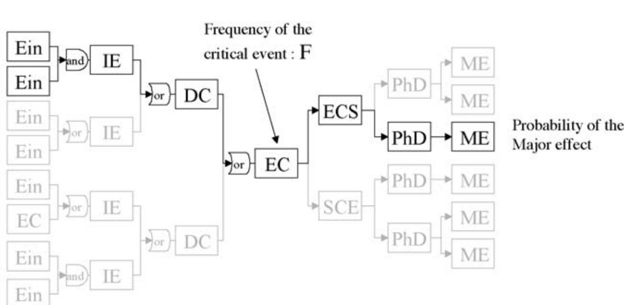

Fig. 3. Bow tie and risk path considered for use in the risk graph. Barriers can apply either on the left-hand side (prevention) or the right-hand side (mitigation).

graphical areas like the Netherlands and are therefore not extendable to the whole Europe. Only very generic frequency ranges could be obtained for the critical events' causes, which hindered the possibility to rely solely on the probability of events.

However, one main objective of ARAMIS was to valorise through contextual frequency data the efforts realised by the operators both in prevention and mitigation. Generic frequencies of critical events are not suitable for that purpose and contextual frequency data is hardly available onsite.

An alternative method was proposed, which focuses on generic values on safety systems and clear guidelines to lower the final frequency of identified scenarios. First, it aims at helping the user with the definition of the safety requirements applying to its plant. These requirements are defined according to the initial risk level without barriers. This means that an initial coarse calculation of the probability is made and that

Table 1
Definition of the levels of confidence in the barriers

Level of confidence in a barrier	Risk reduction factor	Equivalent probability of failure on demand (PFD)	Equivalent probability of failure per hour
4	10000	$\geq 10^{-5}$ to $<10^{-4}$	$\geq 10^{-9}$ to $<10^{-8}$
3	1000	$\geq 10^{-4}$ to $<10^{-3}$	$\geq 10^{-8}$ to $<10^{-7}$
2	100	$\geq 10^{-3}$ to $<10^{-2}$	$\geq 10^{-7}$ to $<10^{-6}$
1	10	$\geq 10^{-2}$ to $<10^{-1}$	$\geq 10^{-6}$ to $<10^{-5}$

a consequence level is assigned to the major effects independently to any vulnerability of the surroundings. Then, the method helps the user to define the safety barriers [10] by promoting the concept of safety function and by providing different possible strategies of barrier implementation for a given safety function.

The frequencies of resulting scenarios are then evaluated from the frequency of the initiating event the probabilities of failure of the different safety barriers implemented, according to principles derived from the SIL concept (safety integrity level) available in IEC 61508–61511 standards [11,12]. Among the scenarios, which result from the application of the safety barriers, only the phenomena that range from 10^{-5}/year to 10^{-7}/year are selected for further calculation of risk severity. These are called the reference accident scenarios (RAS).

5.3. Defining the safety requirements

As it can be understood from the previous paragraph, the definition of the safety requirements is a keystone of the ARAMIS methodology. The proposed method is inspired by the IEC 61508 standard [11]. The idea is to guide the user in the identification of the risk reduction goal that should be associated with different scenarios (Table 1). This approach has a triple interest. It helps the user improving its management of risks by defining clear targets. It helps the competent authorities checking the risk reduction for the same reasons. It provides an evaluation of the residual risks. The way it was built also reduces the stress put on the quality of probability values.

To define the safety requirements, four consequence classes were defined and associated to the major effects independently from the intensity of the considered phenomenon. For example, a fireball will always be assigned a consequence class C4 (irreversible injuries or death outside the site) whereas a jetfire could only be considered as C2 (injuries leading to hospitalisation). The consequence classes also reflect the possibility of domino effects. In this case, the consequence class attributed to a given phenomenon is increased potentially generated by escalation.

The risk graph (IEC 61508) in Fig. 4 sets then the levels of confidence in the barriers which should be applied to reach the safety objective, i.e. the risk reduction goal defined in the matrix, namely to make the risk residual or even negligible. This risk graph takes also into account an exposure frequency parameter (T_1 if the targets are exposed less than 10% of the time T_2 otherwise) and a parameter linked to the capacity to avoid the consequences (kinetics is long enough and emergency measures are robust enough). The frequency classes are linked to the initiating event of the scenario and ranges from P_A ($F < 10^{-4}$/year) to P_D (F > 10^{-2}/year).

Once this work carried out in risk analysis, the resulting dangerous phenomena can then be ranked according to their classes of probability and consequences.

The risk matrix in Fig. 5 has been devised for this purpose. The middle zone highlights the scenarios that can be selected for quantitative modelling then risk severity mapping. The upper zone means that not enough barriers have been implemented and risk cannot be tolerated. The lower zone finally states that enough layers of protection are present in order not to select the scenario. The limits were proposed within the project from our extended review but they should be discussed in principle in each country.

For any risk path (i.e. scenario) composed of a minimal cutset in the fault tree and a branch of the event tree, a couple of exposition level X_i and event probability P_j can be calculated. For each of them, the risk graph proposes a value of confidence class to be reached by the entire set of barriers applied to the risk path. When several barriers are applied on a single risk path, the confidence class is the sum of the individual confidence classes of the barriers.

The bow tie diagrams turn out to be a very powerful tool to communicate about risks, in particular towards non-technicians (managers, politicians, etc.). However building-up a bow tie could become very rapidly quite time-consuming. That is why in the context of ARAMIS, we also searched for a method to select the most appropriate equipment and critical events within an entire plant to build up bow ties upon. This is also part of the MIMAH methodology.

Allocating risk reduction objectives and evaluating explicitly the performance of each safety barriers is a very fruitful work to be performed in risk analysis, especially for the operators. It allows to discuss directly the safety strategies onsite through the architecture and implementation of barriers. The levels of frequency derived from the SIL principles also allow to use quantified data when these exist but also qualitative estimation from work group judgement when no data is available. This allows a maximum flexibility but requires anyway at some stage a consensus about the initiating event frequencies and barrier levels of confidence in order to ensure a minimum variability in the resulting evaluation of scenario frequencies.

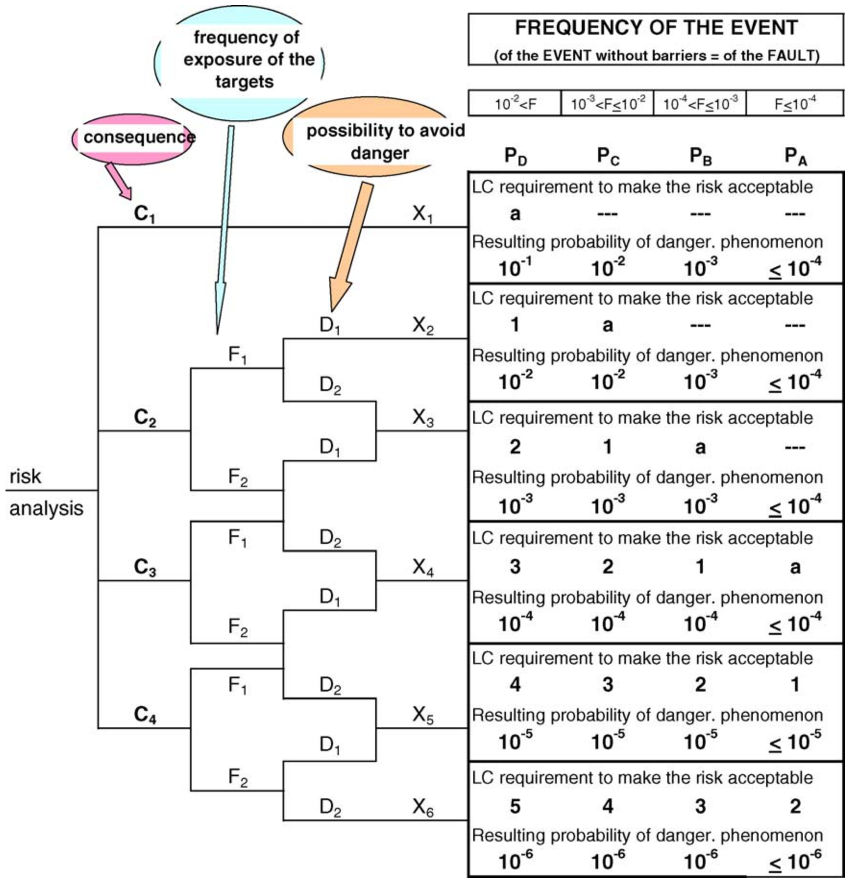

Fig. 4. Risk graph. It determines the required LCs (levels of confidence) to make risk acceptable as shown in Fig. 5 (medium effect).

5.4. Assessing the influence of management and safety culture

The management has a strong influence on the capacity to control the risk. Here again, the interest of ARAMIS is to provide tools to assess the safety management system (SMS) and the safety culture and to allow their taking into account by the competent authorities as well as to help the operators identify the opportunities for improving safety management. The approach in ARAMIS [13,14] consists in devising

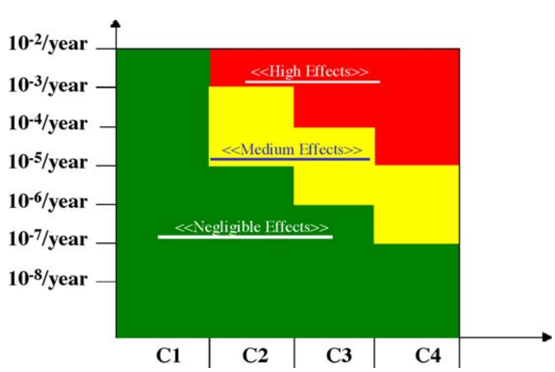

Fig. 5. Risk matrix used for ranking the dangerous phenomena and selecting the reference accident scenarios for the risk severity mapping.

a process-oriented audit protocol focusing on the activities relating to the life cycle of the safety barriers. This life cycle includes design, installation, use, maintenance and improvement activities. For each, 10 important structural elements are evaluated as requirements for the SMS. The outcomes of the audit are then compared to the results of a safety climate questionnaire collected from employees in order to get a contextual level of confidence, in particular regarding behavioural barriers. The questionnaire is made up of 11 cultural factors that characterise a company's safety culture.

Among them are, for example, questions about the reporting of accidents and the willingness to report or the perceived causes of accidents and the perceived responsibilities in the plant or issues about trust and fairness and work and social relations.

At the previous step, each type of barrier is given a generic level of confidence indexed on its probability of failure on demand. These indicative values require then to be adjusted from the local context where they are implemented and maintained. For instance for a behavioural barrier, we would like to adjust the generic confidence in the barrier depending on whether the operator knows the stakes of his actions, or his decisions require complex diagnosis, conflict with production. The aim of the project was also to aggregate the results from the auditing and use of questionnaires into a final score for adjusting – possibly lowering – the generic values into contextual ones.

This link and the whole scoring process is obviously an ambitious goal and still needs to be worked out in the project. The case studies already help getting some benchmark between different types of management and allowed eventually to propose a set of "minimum requirements" for both the culture and management system in order to anchor a first scoring scale. This remains however an important area of research.

5.5. Risk severity assessment and mapping

Each reference accident scenario (RAS) is defined by an initiating event that leads to a critical event, which can potentially lead to different dangerous phenomena. For each phenomenon, a specific severity index has been defined [15,16,17]. The aim is to measure and compare the severity of any dangerous effect with a single scale ranging from 0 to 100. This should allow the comparison of risks of different nature. Depending on the phenomenon, different severity levels were associated to different amplitudes of the considered phenomenon.

Table 2 presents an example of severity values associated with intensities of dangerous phenomena. The user is free to use any model she/he considers relevant for modelling intensity along distance.

One major difference between ARAMIS and usual quantitative risk assessment is the purpose to study separately the vulnerability and the severity from the potential accident scenarios. In this respect, it is not possible to use any Probit function to quantify the severity but had to define thresholds for each phenomenon (Table 2) in order to characterise intensity. Even though these thresholds can sometimes be derived from Probit functions (thermal load and toxic load), they above all require consensus first from the competent authorities of the Member States, which is not the case for the moment.

For each RAS, a risk severity map is then produced. Risk severity is defined for one scenario as the combination of the level of frequency with the intensity of the effects. The combination of risk severity with the vulnerability of the targets produces the actual risk. Risk severity can be represented for each scenario in a geographical way, as a function $S_{\mathrm{RAS}}(d)$ of the distance from the source term

$$S_{\mathrm{RAS}}(d) = \sum_{i=1}^{n} P_{\mathrm{DP}_i} S_{\mathrm{DP}_i}(d) \quad (1)$$

In this equation n is the total number of dangerous phenomena (DP) associated to the RAS; P_{DP_i} is the probability of occurrence of each DP_i; and $S_{\mathrm{DP}_i}(d)$ is the specific severity index associated to the DP_i.

The final mapping of risk severity is then obtained by multiplying the frequency of each RAS with its specific risk severity index

$$S(d) = \sum_{i=1}^{n} f_{\mathrm{RAS}_i} S_{\mathrm{RAS}_i}(d) \quad (2)$$

where n is the total number of dangerous phenomena considered taking into account all RAS corresponding to the installation. More elaborated formulas were proposed for anisotropic risks.

Risk severity mapping as it is defined makes sense and gives very useful information to a decision-maker to elaborate relative priorities for land-use or emergency planning purposes. It also makes sense to disconnect the vulnerability study from the hazardous installation for the same reasons. However, the range of values obtained with such an approach still requires to be interpreted.

5.6. Assessing the vulnerability

The last innovative attempt from ARAMIS is to address the vulnerability of the environment independently of the hazardous site [18,19]. This has the fundamental interest of allowing the local authorities to take useful decisions to reduce the global risk level by reducing the vulnerability whereas the plant operator only can act on the potential hazard of the installation.

The vulnerability is calculated on the basis of a multicriteria decision-aiding approach. With the development of new ways of governance involving local population in risk-informed decisions, the main interest of this approach is to base the vulnerability study on any stakeholder risk perception through expert judgement elicitation. On a given spot of the environment, the vulnerability is thus characterised by the number of potential targets and their relative vulnerability to different phenomena. The global vulnerability is a linear combination of each target vulnerability

$$V_{\mathrm{global}} = \alpha V_{\mathrm{H}} + \beta V_{\mathrm{E}} + \gamma V_{\mathrm{M}} \quad (3)$$

Then, each type of vulnerability is a linear combination of the vulnerability to each type of effect

$$V_{\mathrm{H}} = \alpha_1 V_{\mathrm{H}}^{\mathrm{surp}} + \alpha_2 V_{\mathrm{H}}^{\mathrm{tf}} + \alpha_3 V_{\mathrm{H}}^{\mathrm{tox}} + \alpha_4 V_{\mathrm{H}}^{\mathrm{poll}} \quad (4)$$

For each effect, the vulnerability is a linear combination of vulnerabilities on different types of impact (health, econom-

Table 2
Severity levels associated with different intensities of effects

S_{DP_i}	Overpressure (mbar)	Radiation ($\mathrm{W/m^2}$)
0	0	1
25	30	1800
50	50	3000
75	140	5000
100	250	8000

ical, psychological impact)

$$V_{\mathrm{H}}^{\mathrm{surp}} = x_1^{\mathrm{H}} V_{\mathrm{H}}^{\mathrm{surp,san}} + y_1^{\mathrm{H}} V_{\mathrm{H}}^{\mathrm{surp,eco}} + z_1^{\mathrm{H}} V_{\mathrm{H}}^{\mathrm{surp,psy}} \quad (5)$$

For each type of impact, the vulnerability is also a linear combination of the numbers of different types of target components. For example, the human target is composed of staff onsite (H_1), local population (H_2), population in an establishment receiving public (H_3), users of transportation ways (H_4)

$$V_{\mathrm{H}}^{\mathrm{surp,san}} = a_1^{\mathrm{H\,surp,san}} H_1 + b_1^{\mathrm{H\,surp,san}} H_2 + c_1^{\mathrm{H\,surp,san}} H_3 + d_1^{\mathrm{H\,surp,san}} H_4 \quad (6)$$

The quantification factors H_i are normalised to fit into a 0 to 1 scale.

The application of the methodology has generated a questionnaire that can be used or adapted very locally to elicit from any stakeholder judgement their own perception of vulnerability. The equations have been then interfaced to GIS tools (geographical information system) (MapInfo, ArcView and Geoconcept) for easiness of target inventory and quantification. The GIS allow a very quick mapping of perceived vulnerability (Fig. 6).

The tool is very flexible and offers a large range of available maps considering the type of decisions to be taken: per type of target, per type of effect or overall maps. Fig. 6 shows an example of human vulnerability drawn from the available land-cover information.

Even though it is interesting to base the vulnerability study from the stakeholders risk perception, the outcomes (i.e. the quantification factors) can be discussed. For a relevant discussion, a sensitivity study should have been carried out within the project but it was not the case because of the lack of time within the project. The case studies was used to some extent for that purpose but was not developed in-depth enough to get precise answers during the project.

6. Case studies

When ARAMIS had reached a certain degree of completeness, case studies were carried out to assess the methodology. The case studies had several complementary objectives. The first one was to check the applicability of the method. This implied to assess the capacity of the method to be understood by the users. The different modules of ARAMIS were developed by partners of different European countries and different scientific or industrial cultures. It was a big challenge that the global method be understood and applied by plant operators, competent authorities and local authorities of any country in Europe.

An other important issue was the availability of the data needed to perform the risk analysis. A particular focus was put on frequencies of events for which it was very difficult to obtain trustable generic data, and on data related to the confidence levels of safety barriers. But the same could be true with the geographical information required for the evaluation of the vulnerability, or even information on the process needed for the calculation of consequences.

A third important aspect was the global coherence between modules. Different partners developed the modules of the method and, despite a good communication during the development process, only the case studies could give the evidence that the outputs of one module really are an input to the next module.

Beyond the applicability, the case studies also considered the efficiency and the relevance of the whole methodology.

6.1. It involved comparing ARAMIS with already existing risk analysis methods

It was important to check whether the results obtained with ARAMIS were significantly different from those obtained with other methods. Even if no other method has the same level of integration as ARAMIS, which treats in a consistent way all the process of risk management from the source to the vulnerable environment, it is important to check that basic

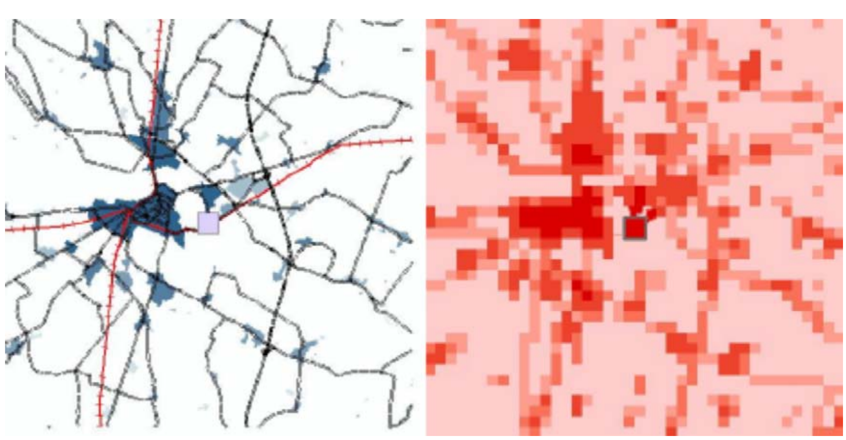

Fig. 6. human vulnerability map (right) obtained from the land cover information (left).

Table 3
Test sites selection for the case studies in 2004

	Country	Main activities
Site A	France	Paper pulp and sheet production plant, upper tier
Site B	Denmark	Oil and gas refinery, upper tier
Site C	The Netherlands	Chemical plant, upper tier
Site D	Czech Republic	Petrol, gas-oils and fuel-oils storage plant, upper tier
Site E	Slovenia	Chemical plant handling ethylene, upper tier

needs covered by traditional tools are also well addressed by ARAMIS.

6.2. It also involved assessing how ARAMIS was answering the needs of the end users

Could the results be easily exploited? This question was of course a major one. As mentioned in Section 1, ARAMIS has several potential users with different needs. A key aspect of the methodology was to answer these different needs with a unique method because all actors need to be able to communicate and discuss on common results and information. To answer satisfactorily this question, the case studies took place in different national and industrial contexts. In each situation, the expectations of the local actors were characterised. These will be discussed in the next paragraph.

- *Is the method adapted to different types of industries, different sizes of plants ?* SEVESO II sites can have very diverse activities and configurations. The composition of the case study set aims at reproducing this diversity.
- *Is the method adapted to different national contexts?* As a European Methodology, ARAMIS must comply with the requirements and uses of all the countries of the European Union. A particular focus is put on the newly integrated countries [20] where industrial risk issues may differ from those in the western part of Europe.

6.3. Sites and contexts of the case studies

Five establishments were chosen in five different countries: Czech Republic, Denmark, France, The Netherlands and Slovenia (Table 3). Each of these countries has its own culture for risk assessment and risk management and faces particular stakes in prospect of a convergent European methodology. France and Denmark have a rather deterministic approach, which has shown some limits. The approach does not allow for flexibility and does not give the opportunity to enforce land-use planning regulations appropriately. The Netherlands is in a different situation. The country has been for a long time a pioneer of the risk-based approach. But the outputs of risk assessment (risk contours or *F–N* curves) are difficult to visualise then to communicate upon towards decision-makers. For both countries, a barrier-based approach and a distinct mapping of risk severity vs. vulnerability is easier to communicate and structure local negotiation among stakeholders. Czech Republic and Slovenia joined the European Union in May 2004 and face different challenges in applying the SEVESO II directive.

The industrial sites were also of different kinds:

- A refinery, where fire and explosion hazards will prevail.
- A chemical plant, with hazardous reactions and storage of chlorine and phosgene.
- A chemical plant using ethylene with polymerisation hazards as well as fire hazards.
- A paper mill, with explosion and toxic hazards.
- A hydrocarbon storage facility, with fire and VCE hazards but simple process.

These case studies were only a first step to assess the exhaustiveness of the method by checking whether it can apply to different types of activities and industrial cultures. It also showed to a limited extent the capacity of the method to answer different local needs such as competent authority control or land use planning.

6.4. Results

The first feedback on the application of the method was globally positive and some of the remarks helped to adjust and improve the whole methodology or the links between the four technical work packages. Other remarks also helped to show the limitations of the method or some warnings that should be given to further users.

The main results from the case studies are summarised below and classified according to the work package that contributed to the production of the concerned elements of the methodology.

6.4.1. MIMAH and MIRAS

MIMAH and MIRAS are the central components of the methodology as their most significant results are the identification of the scenarios, the safety barriers and the reference accident scenarios, that serve as input to the management and severity calculation steps of the methodology. MIMAH is also the part on which the users will spend more time and energy.

The case studies have shown that the description of the method and the tools provided such as the generic fault and event trees or the generic lists of safety barriers were useful and of real support to the risk analyst [21]. However, it showed that they should not be used blindly and that some precautions should be taken especially during the phases where decisions to consider or not equipments or scenarios were taken for the selection of hazardous equipments and the selection of the reference accident scenarios. Both are crucial steps sensitive to uncertainty of the data. The methodology relies on the data collected in the plant. Collaboration with the plant operator is essential to obtain the right information.

The generic trees defined in MIMAH seemed convenient and easy to use. Nearly no additional direct causes have been found during risk analyses. But the generic fault trees should not be used blindly. Even if the list of direct causes (the first two levels of the fault trees) was exhaustive, it was not the case for the list of detailed direct causes or undesirable events (the fourth and fifth levels). The generic fault trees had to be completed to obtain the specific fault trees of the plant. However, this should not be considered as a drawback as the methodology should not completely suppress the reflection of the work group.

The assessment of the frequency turned out not to be easy because of a lack of data. The generic frequencies of critical events such as those provided by existing databases were not easy to use because of the lack of information about the type of industry they applied to and the state of the art they refer to. By using generic data, the risk analysis team with the plant operator could determine the frequency of each initiating event. But there was also a great uncertainty about these data, which led to the conclusion that specific plant data should be preferred to generic frequencies. A great number of initiating events are related to human errors. There is obviously a lack of data in this field.

Safety barriers checklists were very useful to identify actual safety tools during the discussion with the plant operator. The assessment of "design" level of confidence (LC) of barriers was also sometimes difficult.

Concerning MIRAS, the main feedback was that the use of the risk matrix as a decision tool to select the reference accident scenarios should not be used blindly to exclude scenarios close to the limit. One can always choose to model a scenario located in the green "negligible" zone if it is believed necessary to do so. At the very worst, this will only be time consuming but also offer the possibility to appreciate the real impact of questionable scenarios.

6.4.2. Assessment of the influence of the management

During the case studies, the management and safety culture of the test sites were audited [22]. The results served to establish a first reference to which further audits of industrial plants should be compared.

The audits were perceived by the concerned plant operators as a useful tool even if the preparation required prior to the audit was underestimated and the analysis of the SMS and the barrier selection for audit require many efforts.

The barrier typology, developed to identify more precisely the elements of the safety management system that may have an influence on the efficiency of the safety barrier, needs attention as it was sometimes difficult for the plant operators to clearly classify the barriers in the appropriate category.

The calibration is also difficult and, therefore, it is sometimes hard to compare the results produced by different audit teams. This is the reason why the following recommendation was made in the ARAMIS User Guide [7].

"It should be stressed, that the qualitative results of the audit may be more relevant to the company (and other stakeholders, like the competent authorities) than the quantification, as the qualitative results provide immediate information on specific safety management issues that can be improved or should be altered."

6.4.3. Severity calculation

The case studies have shown that the complete methodology is applicable and the GIS tools are useful and operational and allowed the drawing of severity maps from the results of the risk analysis. But the case studies have also stressed that the method and the interpretation of the results are not easy tasks and require some expertise. Indeed, as it could be expected, the severity mapping is very much influenced by the results of WP1 (MIMAH and MIRAS). The number of equipment, RAS and DP considered influences the value of S, as the severity index reflects the total hazard that the plant can produce. When only part of the equipments are considered, the meaning of the global S index can be questioned.

But the difficulty did not come only from the method. The interpretation of the severity maps requires that the risk decision context is adapted to this new tool that combines the probabilities and intensities into one single value. In other words, in several case studies, the severity index was a new way to measure risk, different to the previously used approaches that had proved to be inefficient. Both the local authorities and plant operators had difficulties to interpret the results. This situation should evolve with time and the familiarisation of the actors with semi-probabilistic approaches.

6.4.4. Assessment of the vulnerability and mapping

The assessment of the vulnerability was made easy with the GIS tools, but the case studies have shown that it was necessary to have pertinent databases to obtain expected results. The availability of the geographical databases may be a difficulty in some countries of the European Union. Sometimes, several databases are available with different types of formatting and presentation of the data. Some expertise is needed to ensure the selection of the most appropriate database.

The training of the users is also necessary to ensure that they understand the vulnerability concept and how it was implemented in the ARAMIS methodology, that they used the appropriate data and that they understand how to use the results for decision-making. As for the severity, the use of the vulnerability is very much linked with the regulation in force about land-use planning.

7. Research issues emerging from the ARAMIS project

The risk assessment method described in this paper, ARAMIS, is the result of a voluntary step towards a harmonised approach of risk analysis on SEVESO II industrial sites. ARAMIS has the ambition to solve some of the difficulties encountered with traditional approaches by providing very practical tools in an integrated methodology. But the ARAMIS project also pointed out the need for an increased research effort in a series of specific fields that were not initially planed in the project itself.

The first of them is linked with the difficulty to find reliable data for the calculation of accident probabilities. Even if the solution proposed in ARAMIS, the barrier approach, reduces the consequences of such a lack, a lot could be done by unifying the efforts of the industry and research institutions to build accessible databases containing useful information that would be complementary to traditional reliability databases.

The quantification of the influence of management on the probability of accidents is also a key question, which was not fully resolved in the course of the project.

A third field of research relates to the evaluation of vulnerability. ARAMIS already proposes an interesting definition of vulnerability and a set of screening tools to build vulnerability maps. A next interesting task could be to provide more detailed tools to help decision-makers identify what can be done explicitly to reduce the vulnerability.

Other questions were raised by the project such as the definition of the unique risk severity index, which implies to be able to compare different types of effects among them. Suggestions were made in the framework of ARAMIS. But the project also highlights the remaining questions and lack of common agreement on many effect thresholds. The interest of ARAMIS is also to provide the right frame to define both requirements and means of valorisation for this future research.

8. Conclusion

The ARAMIS methodology was briefly described in this paper based on the information detailed in the ARAMIS User Guide [7]. It aims at offering an alternative way to the traditional risk-based and consequence-based methodologies for risk analysis by providing a series of integrated tools. These were designed to answer the specific needs of potential ARAMIS users who are industry, competent authorities and the local authorities. They were also elaborated to solve some of the difficulties raised by the lack of reliable data, namely concerning the accident frequencies. By promoting the barrier approach, ARAMIS helps the users to define the safety requirements, which apply to the studied plant, and therefore helps the competent authorities to verify the explicit control of risk by the operators. This approach also allows an easy and explicit identification of the reference accident scenarios, making the communication between the stakeholders easier or at least more straightforward and structured. The same should be true with the approaches of the severity and the vulnerability, which are exploited through a clearly understandable graphical representation.

Five case studies, that have taken place in five European industrial sites, have confirmed the achievement of these goals and helped resolving some of the difficulties, which remained for a complete integration of the method.

Eventually, ARAMIS also sets the framework and the objectives of future research on diverse specific fields among which are the production of reliable accident frequency data, the quantification of the influence of management on the accident probability, the vulnerability reduction options or the effect threshold definition.

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