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Benchmarking on the evaluation of major accident-related risk assessment

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ABSTRACT

This paper summarises the main results of a European project BEQUAR (Benchmarking Exercise in Quantitative Area Risk Assessment in Central and Eastern European Countries). This project is among the first attempts to explore how independent evaluations of the same risk study associated with a certain chemical establishment could differ from each other and the consequent effects on the resulting area risk estimate. The exercise specifically aimed at exploring the manner and degree to which independent experts may disagree on the interpretation of quantitative risk assessments for the same entity. The project first compared the results of a number of independent expert evaluations of a quantitative risk assessment study for the same reference chemical establishment. This effort was then followed by a study of the impact of the different interpretations on the estimate of the overall risk on the area concerned. In order to improve the inter-comparability of the results, this exercise was conducted using a single tool for area risk assessment based on the ARIPAR methodology. The results of this study are expected to contribute to an improved understanding of the inspection criteria and practices used by the different national authorities responsible for the implementation of the Seveso II Directive in their countries. The activity was funded under the Enlargement and Integration Action of the Joint Research Centre (JRC), that aims at providing scientific and technological support for promoting integration of the New Member States and assisting the Candidate Countries on their way towards accession to the European Union.

1. Introduction

This paper summarises the main results of a European project BEQUAR (Benchmarking Exercise in Quantitative Area Risk Assessment in Central and Eastern European Countries) that was conducted by the Joint Research Centre (JRC) of the European Commission (EC) in collaboration with a team of experts from new EU Member States between 2004 and 2007. The activity was funded under the Enlargement and Integration Action of the Joint Research Centre (JRC), which aims at providing scientific and technological support for promoting integration of the New Member States and assisting the Candidate Countries on their way towards accession to the European Union.

This project represents the third in a series of JRC benchmarking studies on major hazards of establishments falling under the Seveso Directive [1–3]. These studies were launched in order to explore the state-of-the-art in the process of risk assessment, which is an essential aspect of a chemical establishment's safety report as defined by the Seveso II Directive [4]. Their findings represent important new information on implementation of the Directive of the Member States, in particular, a clear overview and improved understanding of the different practices, methodologies and tools in use within the different EU Members States for this purpose. In addition, the results pinpointed some of the main sources of potential uncertainty in these assessments, confirming at the same time that each phase of the risk assessment process is subjected to a high degree of uncertainty.

The first benchmarking exercise, the Benchmark Exercise on Major Hazard Analysis (BE-MHA) [5,6], was conducted during 1988–1990. The focus of the exercise was an ammonia storage facility, which, during the exercise, was analysed by eleven different teams of experts, representing control authorities, research organisations, engineering companies and industry. The study produced an independent assessment of the risks in the reference facility and resulted in a comprehensive overview of currently available methodologies for industrial risk assessment in Europe. It ultimately led to the conclusion that: (i) further work is necessary to reduce the inherent variability that is typical of any risk assessment process; (ii) the role of expert judgement is fundamental in any

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risk assessment process; (iii) there are clear limitations to the risk models adopted, which should be used for their specific purpose only; (iv) research priority should be given to the development and validation of more consistent models for the description of ammonia accidental release.

As a follow up of the benchmarking some “models' evaluation groups” were established, with the primary objective of defining criteria for the applicability of consequence models [7], and a number of years later an opportunity arose to launch a second benchmarking exercise to re-assess the situation. The second exercise was named ASSURANCE (Assessment of the Uncertainties in Risk Analysis of Chemical Establishments), and was conducted from 1998 to 2001 [8,9]. This benchmarking aimed at improving the understanding of uncertainties associated with the risk analysis. Seven different teams executed an independent analysis of risks associated with an ammonia storage facility, located in a hypothetical site, considered as the reference establishment. Again the exercise contributed to increase awareness of the intrinsic uncertainty present within the risk assessment process and it helped to identify some of the main sources of uncertainty. More specifically, the hazard identification phase was addressed as a very critical aspect and it was emphasised that probabilistic and deterministic approaches can lead to quite different ranking of the postulated scenarios. This was particularly evident for those scenarios characterised by less severe consequences. The estimate of scenarios' frequency was quite inconsistent amongst the teams although less divergence was present among those having made use of the probabilistic approach. Large differences were also observed with the calculation of the consequences: the outflow of ammonia from a leakage, the dispersion of the released ammonia and the health effects on humans exposed to the toxic gas, gave the greatest problems. Nevertheless the analysis of the above discrepancies has allowed the development of a report providing a qualitative assessment of the particular importance of uncertainties in assumptions, data and calculation methods to the risk estimate. This assessment continues to be useful as a guide to areas where, in particular, caution must be taken when performing and interpreting risk analyses.

A point to note is that both of the first two benchmarking exercises were conducted from the viewpoint of risk analysts with experience in the elaboration of Seveso safety reports, and as such represented more or less a plant operator's perspective. In both projects, moreover, the benchmarking consisted of an independent analyses of the same reference establishment, and covered all the different aspects of the risk assessment process, including: (i) the description of potential accident scenarios, (ii) the likelihood of their occurrence and (iii) the assessment of their consequences on human beings (i.e., source terms and damage curve calculations, and vulnerability assessment). The large variability of responses by the benchmarking participants for all the different steps of the risk assessment process clearly demonstrated the complexity of the risk assessment process and the inherent uncertainty associated therewith.

2. Purpose and structure of the benchmarking

2.1. General

In order to appraise whether a discrepancy of opinions similar to those of the previous benchmarking could also be found in the process of reviewing a risk assessment, it was decided to launch a third benchmarking exercise, whose description is the object of the present paper. Review of the risk assessment is a typical responsibility of the competent authorities, and their inspectors who, with reference to article 18 of Seveso Directive, are required to review the safety reports of establishments falling under the Directive. In order to address this issue from a competent authority perspective, the benchmarking was structured in such a way to consist of a re-assessment, by independent reviewers, of an existing risk assessment, and the following analysis of the possible discrepancies amongst the different responders. The selected chemical establishment used as the reference plant was an existing lower tier Seveso establishment and, for the purposes of this exercise, a mock version of the original risk assessment was used. This mock version, hereafter referred as the ‘reference analysis', was generated by reworking the original data, assumptions and calculations used in the original safety report of the reference plant and ‘relocating' the plant to a different environment. These measures were specifically intended to avoid any possible correlation of the results of this benchmarking with the actual risks associated with the existing plant.

The participants in this benchmarking study were a heterogeneous group, consisting of representatives of competent authorities from the Member States within EU-12,[1] with responsibilities associated with the implementation of the Seveso Directive in their countries. Risk assessment experts working in research organisations were also represented in this group. All risk experts were explicitly asked to provide their feedback at different stages of the risk assessment process by taking into consideration the particular perspective and concerns of the competent authorities within their country.

The main purpose of the benchmarking study was to explore how independent reviews by individual experts of the same risk assessment might differ in their findings and conclusions, and how these differences subsequently might influence the calculation of risk estimates associated with a particular zone of impact in the area surrounding the plant. By focusing the study on the review of an already completed risk assessment, and its implications for a particular impact area, the benchmarking study represented an approach to analysing risks of a chemical establishment closely aligned with the competent authority perspective. In this sense, the project differed significantly from previous benchmarking studies coordinated by the JRC that focused on the independent execution of the risk assessment itself (rather than the review), by different teams of experts.

2.2. Benchmarking objectives

The main objectives of the BEQUAR project were:

- to conduct independent reviews of the same risk assessment of a particular hazardous establishment (reference establishment), as re-elaborated from its original safety report;
- to assess the impact of the risk of the reference establishment on the overall area affected by potential accidents, and to make a first attempt to analyse how different reviews/interpretations of a specific risk study might be reflected in the different estimate of area risk.

The main intention was to offer a general perspective on how independent reviews of the same risk assessment, which are conducted from the competent authority's standpoint, might differ from each other and be reflected in a different understanding of the risk associated with a certain Seveso-type establishment. The outcome of such an analysis has the evident advantage of contributing towards a better understanding of the approaches and the

[1] The EU-12 refers to the countries that entered the EU after 1 May 2004.

current practices used by the different national authorities and how these choices might have different technical, social and economic impacts.

The participants in this benchmarking were mainly representatives of the competent authorities belonging to the European Union newly associated and candidate countries (see Appendix A). During the project execution they played the role of: (i) inspectors responsible for the evaluation of the risk assessment conducted by the operator of the selected establishment, and (ii) decision-makers, having to assess the impact of the selected industrial site on the overall area risk.

2.3. Reference establishment

The industrial establishment used as the reference plant for the BEQUAR project belongs to an existing international food-processing company, which produces starch, dextrose, glucose syrups, isosugars, alcohol, and feed products using maize as main raw material. This plant makes use and produces dangerous substances exceeding the qualifying quantity of Column 2 of Annex I of the Seveso II Directive, which determines the automatic application of Art. 6 & 7 (low-tier establishment) [2]. Specifically, the involved substances are: (i) liquid *sulphur-dioxide* used for the stepping process, and (ii) *ethanol* produced by the company and stored in different locations.

The installations considered as more critical for their potential off-site effects and, therefore, to be submitted to complete risk assessment were identified through a screening method [11]. The selected installations were:

(1) *Tank wagon unloading station*: containing sulphur-dioxide (SO_2), which in case of accident could lead to release of this toxic substance into the environment. The unloading station is designed to allow the operation of one tank wagon at a time (every month). This station is characterised by a 15 m long concrete platform with mesh screen for protection.
(2) *Storages of ethanol*: which in case of loss of containment could lead to fire and explosion (hereafter referred as tanks Tn with $n = 1, \ldots, 6$). Loading of ethanol is continuous (12 h). Automatic closure of the valve and stopping of the pump is activated in case of overflowing. The tanks are of cylindrical shape which are assumed to be 100% full of liquid ethanol under environmental conditions with temperature maintained through external water-cooling by 20 °C during hot summer time. All tanks are characterised by external concrete walls, designed to contain the complete tank contents in case of accidental release.

2.4. Benchmarking outline

The risk assessment data submitted for review were extracted from the safety report of the reference establishment. However, some of the original data, assumptions and calculations used in the original safety report were intentionally re-manipulated to avoid any possible correlation of the benchmarking results with the actual risks associated with the existing plant. In addition, it was intentionally decided to artificially replace the environmental setting of the plant, its local vulnerability, and its population density. All these measures have been taken in order to guarantee anonymity of the selected plant and in order to prevent that any outcome of the benchmarking might be misinterpreted in terms of actual risk associated with the existing plant and surrounding area. Rather, the exercise assumed that the reference plant was located in proximity of an urban area with a high population density and flat terrain. Virtual local data on population distribution and population presence were taken into consideration for use in social risk calculations (FN-curves).

A point to note is that, in order to improve the inter-comparability of results, the risk assessment study was conducted and presented by using a single tool for area risk assessment, based on the ARIPAR methodology [12–16]. ARIPAR is a quantitative area risk assessment tool used to evaluate and aggregate the risks resulting from different sources, including hazardous substances that are stored, processed and transported, in a defined area. It is based on a geographical information system (GIS) platform running under different versions of MS-Windows. The application of ARIPAR requires the quantification in terms of frequency and consequence of all significant accident scenarios for fixed installations and for the transport of dangerous substances. It is based on a set of procedures designed to determine – through the combination of the occurrence frequency of postulated accidents and their associated consequences (i.e., on-site and off-site causalities) – local, individual risk and societal risk.

2.4.1. Documentation phase

A set of documents containing all relevant information of the reference plant and its installations were distributed to the participants in the benchmarking. The documents contained: (i) *territorial data* (i.e., topographic map of the fictitious site, meteorological conditions and atmospheric stability, population density and distribution), (ii) *establishment data* (detailed description of the installations, layout diagrams, process and instrumentation diagrams), and (iii) risk assessment data (i.e., hazard identification analysis, frequencies of accident scenarios with information on existing mitigation measures and devices and related reliability and availability, source terms, damage profiles for each accident scenario, and vulnerability data). A visit to the premises of the reference establishment was also organised. All relevant data extracted from the produced documentation were uploaded into the ARIPAR software and distributed to the benchmarking members.

2.4.2. Working phase I

In the first phase the participants were asked to review all the risk assessment data provided within the documentation. The reviewers conducted this activity independently, by using their own personal experience, judgment, data, and tools. They were given the possibility to modify the revised data directly within the software system used for the risk calculation (ARIPAR) in order to have an overview of the effect of their assumptions on the overall estimated risk for the plant. The focus of this reviewing activity was on the completeness and consistency of the postulated scenarios, the frequency of the top events and the effectiveness of mitigation measures, the appropriateness of the source terms, and the vulnerability data used for consequence assessment (i.e., probit data).

The modelling calculations concerning the accident damage profiles were excluded from the scope of the present project, and therefore, they were not considered in the review process. This was due to the fact that the majority of the benchmarking participants, who represented safety authorities within the EU-12, were not in possession of full or short-cut model tools that are normally necessary for such calculations.

2.4.3. Working phase II

In the second working phase, the different reviews conducted in the first phase were compared. This activity was particularly important to confront the different approaches adopted for evaluating a risk assessment (databases, methods, procedures, models), and to fully explore the variability of independent reviews, conducted by

Table 1a
List of postulated SO_2-related scenarios: short description (TW stands for tank wagon unloading station)

Scenario	Description	Causes	Outflow
SO_2-related scenarios (tank wagon unloading station)			
TW111	54 t SO_2 release as a consequence of the catastrophic rupture of the TW	Mechanic impact (hydrochloric acid or alkali tank wagon, 26 times per year)	Instantaneous two-phase release of the whole TW content at once.
TW211	54 t SO_2 release as a consequence of the catastrophic rupture of the TW	Mechanic impact during tank wagon change (10 times per year)	Instantaneous two-phase release of the whole TW content at once.
TW221	Not isolatable leakage of equivalent Ø 40 mm at the flange connection	Failure in the flange connection to the uploading station AND failure of the tank wagon valve	Vertical two-phase release during 10 min (time required for mounting the shut-off valve) with mass flow rate of ca. 8.8 kg/s at the height of 4.35 m.
TW121	Isolatable leakage of equivalent Ø 10 mm at the flange	Flange leakage	Horizontal two-phase outflow during 20 min (time necessary for detection and intervention) with mass flow rate of ca. 1.8 kg/s at the height of 4.35 m.
TW131	Isolatable leakage of equivalent Ø 25 at the flexible pipe	Flexible pipe-end rupture AND failure of the protection valve (spring valve)	Vertical two-phase outflow during 20 min (time necessary for detection and intervention) with mass flow rate of ca. 3.9 kg/s at the height of 5 m.
TW151	Not isolatable leakage at the flange	Flange leakage AND tank wagon valve failure	Horizontal two-phase outflow of equivalent Ø 10 mm during 20 min (mass flow rate of ca. 1.8 kg/s) at the height of 4.35 m; afterwards, vertical two-phase outflow from Ø 40 mm for 10 min (time required for mounting the shut-off valve) with mass flow rate of ca. 8.8 kg/s at the height of 4.35 m.
TW161	Not isolatable leakage at the flexible pipe	Flexible pipe-end rupture AND failure of the protection valve AND failure of the tank wagon valve	Vertical two-phase outflow at equivalent Ø 25 mm during 20 min (time necessary for detection and intervention) with mass flow rate of ca. 3.9 kg/s at the height of 5 m.; afterwards, vertical two-phase outflow from Ø 40 mm for 10 min (time required for mounting the shut-off valve) with mass flow rate of ca. 8.8 kg/s at the height of 5 m.

assessors with different experiences and national cultures. In addition, it was a good opportunity to study the role played by the single steps of the risk assessment (scenarios' identification, frequency and consequence assessment) on the final risk estimate, through a very preliminary sensitivity study.

2.5. Postulated accident scenarios

The postulated accident scenarios were taken directly from the original safety report of the reference plant. These were determined through hazard identification analysis, which was presented to the benchmarking participants during the visit to the plant. As the plant was characterised by quite simple processes, the hazard identification analysis was relatively simple. Standard guidewords were not used, and the whole set of parameters, which are typical of process operations of more complex systems, have not been considered. The list of scenarios resulting from this analysis is given in Table 1.

2.5.1. Sulphur-dioxide-related scenarios

The tank wagon unloading station (hereafter indicated by TW), was modelled as a horizontal cylinder 10.5 m long with 3 m diameter, placed at 1.1 m height from the concrete surface. The full tank

Table 1b
List of postulated ethanol-related scenarios: short description for (E stands for ethanol tanks)

Scenario	Description	Causes	Outflow
Ethanol-related scenarios (ethanol storages)			
E1 (Tn)	Catastrophic rupture of the tank Tn. Bunds are, respectively: 1500, 817, 900, 100, 113, 113 m^2, which correspond to the following volume containments: 5000, 2000, 930, 230, 700, 700 m^3	Structural failure	Instantaneous release contained in the bund (A_n = 5000, 2000, 930, 230, 700, 700 m^3)
E2 (Tn)	Not isolatable drainage nozzle rupture in the tank Tn. Discharge velocity depends on the hydrostatic head. Liquid levels are, respectively: 13.2, 10, 4.6, 9.3, 8.9, 8.9 m. Containment bunds as above.	Pipe branch rupture on a not isolatable section	Ethanol release (A_n = 5000, 2000, 930, 230, 700, 700 m^3, $n - 1, \ldots, 6$) Horizontal leak from Ø 80 mm pipe, with average mass flow rate m_n and with outflow time t_n: $m1$ = 24.21 kg/s; $t1$ = 72 h $m2$ = 19.57 kg/s; $t2$ = 35 h $m3$ = 15.69 kg/s; $t3$ = 20 h $m4$ = 14.58 kg/s; $t4$ = 3.4 h $m5$ = m6 = 17.96 kg/s; $t5$ = t6 = 11.2 h

T_n: nth tank (n = 1, . . ., 6); A_n = ethanol content in the nth tank (n = 1, ..., 6).

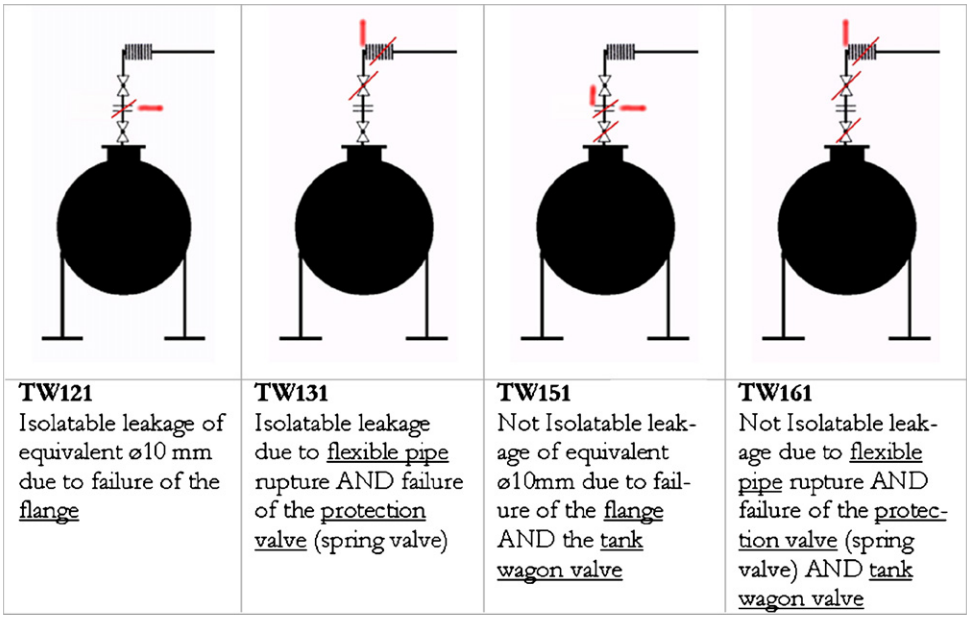

Fig. 1. Tank wagon unloading station: possible failures of components and corresponding accident scenarios.

contains 54 t of liquid SO_2 in the saturated conditions at temperature of 40 °C, which was maintained by external water heating (i.e., saturated water with temperature 120 °C).

The TW system was modelled by considering two main operating phases:

(i) mission start (i.e., arrival of the tank and its connection to the unloading system), and
(ii) *on-line* operation.

For the first case (i), since all events were established to be human-action-related, no mission time was considered. The corresponding postulated scenarios were either associated with a catastrophic event, i.e., the mechanical impact of the tank (TW111, TW221), or due to a possible faulty connection with the unloading station (TW211).

The *on-line* operation (ii) referred to the process of unloading the tank wagon's contents into the plant. The operation was characterised as 10 missions per year with 876 h duration each. The corresponding scenarios were associated with the failure of one or more passive components as summarised and depicted in Fig. 1.

2.5.2. Ethanol-related scenarios

Concerning the 6 ethanol tanks (volumes: 5000, 2000, 930, 230, 700, 700 m^3, respectively), no systems analysis was performed. The involved scenarios were simply: the catastrophic rupture of the tank [E1 (Tn), with $n = 1, \ldots, 6$], and the release due to non-isolatable pipe rupture (E2 (Tn), with $n = 1, \ldots, 6$).

3. Review of the risk assessment: main results

3.1. Introduction

The present section describes the main outcome of the review of the benchmarking participants for the different steps of the risk assessment process. As mentioned in the introduction, the reference analysis submitted for review was generated by reworking the original data, assumptions and calculations used in the original safety report of the reference plant. The complete outcome of this analysis is presented elsewhere [10], however, all the relevant information necessary to understand and to interpret the review process are included in the following sections, which refer to the separate steps of the risk assessment process.

In particular, the following sections represent a digest of the benchmarking reviewers' position with regard to the appropriateness and completeness of postulated scenarios, frequency of accident scenarios with information on existing mitigation measures and devices including related reliability and availability, and accident consequences. A point to note is that the representation of the group position as a whole required some simplifications. Thus, in some cases, the results presented here represent general trends and do not have statistical significance.

3.2. Hazard identification analysis

In general, the perception of the reviewers with regard to the hazard identification analysis was quite positive. The positive response referred to various aspects of the analysis such as the format used, the underlying assumptions, the completeness of the scenarios' list and the quality and level of detail. Amongst the few criticisms raised by the reviewers, the lack of a clear explanation for excluding other possible hazards from the scenarios' final list emerged as the main negative point. These scenarios were actually screened out due to their low likelihood/consequence, but without clear explanation in the hazard identification analysis. In addition, some reviewers also alleged that conclusions within the hazard identification study lacked adequate detail, particularly concerning the definition of measures used to improve safety. (In fact, reviewers noted that prevention and mitigation measures were often mixed up within the study; moreover, their descriptions often lacked the proper level of detail.) Nevertheless, all the reviewers (representing nine countries of the EU-12) declared that the present hazard identification analysis would be considered as acceptable by the safety authorities in their countries.

Particularly interesting is the comparison of the reviewers' positions concerning the credibility of the catastrophic scenarios (Fig. 2a). The highest credibility value was scored by the catastrophic rupture of the SO_2 tank wagon as a consequence of the

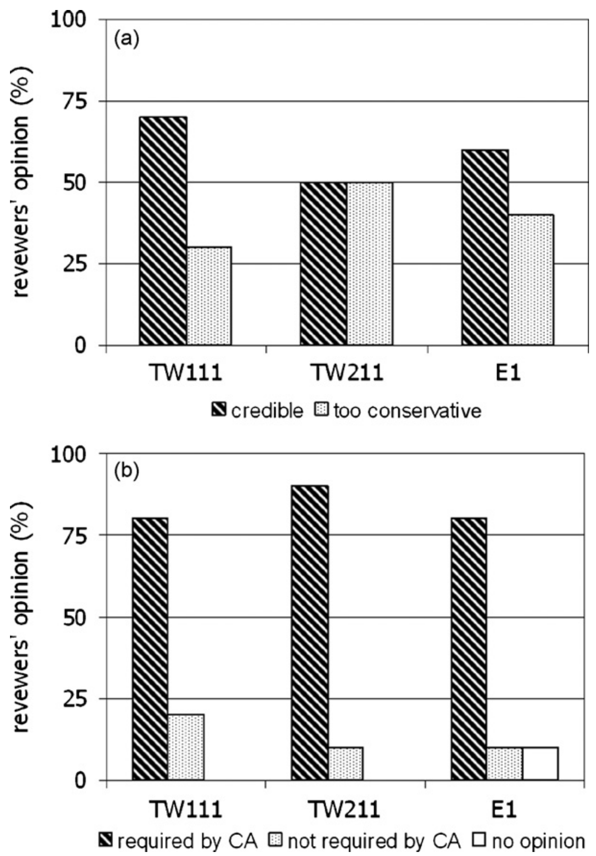

Fig. 2. Reviewers' opinion about the credibility of the catastrophic scenarios (a), and the reviewers' perception whether these scenarios would be required by their national authorities in any case and regardless of their likelihood (b).

impact with the alkali/chlorine tank wagon (TW111). The catastrophic rupture of ethanol tanks (E1) was considered the second credible, while there was an even split (50% very credible–50% not very credible) in reviewer perceptions regarding the catastrophic rupture of the SO_2 tank wagon during wagon change (TW211).

Fig. 2b summarises responses to the question of whether the safety authorities in the reviewers' countries would require a detailed analysis of these accident scenarios regardless of their credibility. The majority of reviewers responded in the affirmative for each of the three catastrophic scenarios, confirming the existing trend among safety authorities that gives particular importance to high consequence/low likelihood scenarios.

3.3. Frequency assessment

The accident frequency data submitted to review were taken from the safety report of the reference plant. However, some of the original input data (i.e., frequency of basic events), assumptions and calculations were intentionally altered by the JRC in order to avoid any possible correlation of the results of this benchmarking with the actual data of the reference plant. In this way it was possible to produce a consistent data set that differed from the original analysis and, therefore, could be the object of an open and unconstrained review.

The benchmarking participants were asked to review the frequency data for each scenario and to provide alternative values when they deemed it necessary. In particular, the review of frequency data involved all aspects of frequency assessment, by including the frequency of basic events, assumptions and calculations. The final outcome of this review was a set of possible alternative data for each benchmarking participant with regard to the frequency of top events. Different sources were quoted by the reviewers, which were used to support their analyses [10]. In some cases they evoked expert judgment to justify their position.

The comparison of the data reviewed by the participants with those of the reference analysis is outlined in (Fig. 3a and b), which refer to the catastrophic and non-catastrophic scenarios, respectively.

For the catastrophic scenarios (Fig. 3a), the benchmarking reviewers demonstrated a clear preference for higher accident frequency values if compared with their reference values, for all sulphur-dioxide-related scenarios (black symbols). A point to note is that these scenarios are driven by human factors-related basic events. For this reason, they were considered as very difficult to assess due to their dependence on a combination of several factors. These factors are company and plant specific (e.g., specific instructions and procedures in use, specific safety culture within the organisation, etc.), rendering any review of this aspect rather difficult for competent authorities. By contrast, for the ethanol-related catastrophic scenarios (white symbols) the response was relatively more uniform and in agreement with the reference value. This scenario is driven by structural aspects and it was thereby considered more predictable.

Similarly to the previous case, the benchmarking participants also preferred higher values of accident frequency for non-catastrophic scenarios (Fig. 3b). This case was also characterised by a higher scatter of responses amongst the different benchmarking reviewers. As expected, the highest scatter was found for the lowest frequency scenario (TW211) due to the high uncertainty associated therewith. A similar situation was found for those scenarios involv-

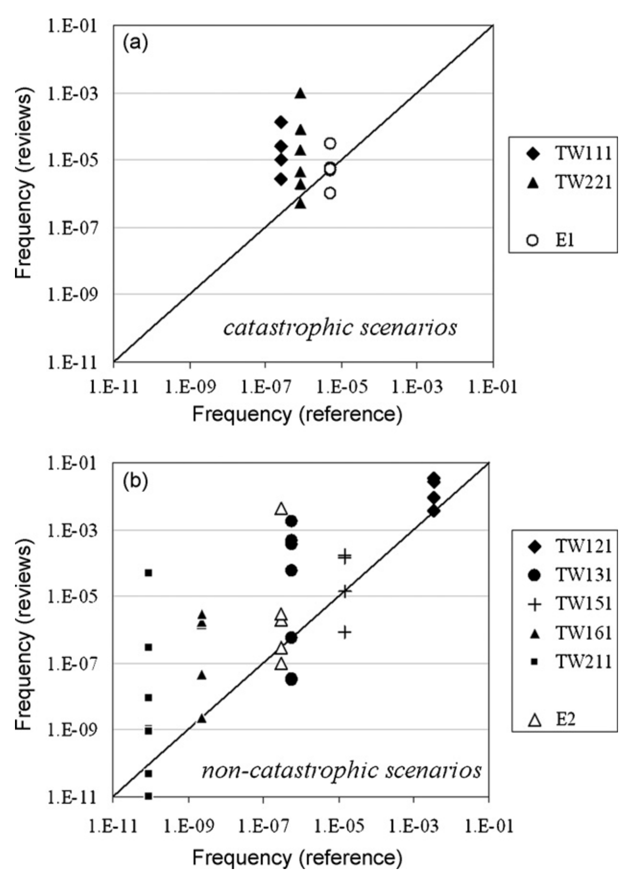

Fig. 3. Frequency of the accident scenarios as assessed by the reviewers vs. reference analysis' frequency data. (a) Catastrophic scenarios; (b) non-catastrophic scenarios.

ing the failure of the flexible pipe component (TW131 and TW161, see also Fig. 1). This fact is attributable to the greater uncertainty associated with this type of component, which in turn is mainly due to the large variation in the data found in the literature. The data related to the frequency of ethanol-related scenarios were also characterised by a very large scatter, probably due to the inadequate clarity of this scenario description, as some of the reviewers lamented.

During discussions at the group's final meeting, the risk consultant, who provided the frequency data for the reference plant's safety report argued that the frequency values proposed by some of the benchmarking participants were often quite unrealistic and that the differences between their preferences and from the reference values actually used in some cases were extremely high. Moreover, he stated that in a number of instances their preferences could, probably not be validated by existing data sources, which implied that some members were making judgements solely on the basis of their subjective views rather than objective evidence. Nonetheless, it was commonly recognised that, although the differences were perhaps a bit excessive for a few cases, uncertainty about frequency values is an ongoing and well-known problem, as also highlighted in the previous benchmarking. In addition, the outcome of this discussion further confirmed that the lack of access to reliable reference databases for evaluating specific process hazards within the competent authorities is a significant obstacle to making informed judgments about the frequency assessments selected by the operators.

3.4. Consequence assessment

For the purpose of the benchmarking, the reference plant had to be 'relocated' in a different environment. Therefore, the original consequence assessment study available in the safety report had to be readapted to the different environmental setting. For this reason, the JRC, with the assistance of the consultant who preformed the risk assessment study for the actual plant, recalculated the entire set of consequence data. This was conducted by making the same assumptions as in the original case but by using different atmospheric data compatible with the fictitious setting where the reference plant was supposed to be located.

Since the benchmarking was conducted under a competent authority perspective, the review of the consequence assessment was restricted to certain specific aspects of this study. In particular, the analysis of the damage curves obtained through modelling of toxic gas dispersion and/or pressure/temperature distributions was excluded from the evaluation exercise. This effort would have required the availability of codes for modelling the calculations, which are not necessarily in the possession of many competent authorities. Rather, the review was carried out on:

(i) the conclusions relative to the '*source terms*', and
(ii) the vulnerability assessment (probit values & threshold limits).

The review of both the source terms calculation and of the vulnerability assessment was conducted by the benchmarking participants through their response to a questionnaire prepared by the JRC for this purpose. In particular, the questionnaire was addressed to get information about the participants' perception on: (i) the validity of source terms calculation, (ii) the acceptability of the adopted methodology, (iii) the presented format, and (iv) the clarity of assumptions. The responders were supposed to provide an answer in terms of multiple-choice options to measure their level of agreement (i.e.: "*totally agree*", "*tend to agree*", "*tend to disagree*", and "*totally disagree*").

For the vulnerability assessment, the questionnaire listed a number of probit values and threshold limits taken from the literature, and the responders were supposed to mark the preferred ones.

3.4.1. Source terms

The outcome of the source terms calculations was presented to the benchmarking participants. For each accident scenarios, the results of mass flow rate (kg/s) were provided as a function of time by considering as time zero the beginning of the accident release. For sulphur-dioxide scenarios, the mass flow rate was quite constant over time with average values reported in the 'outflow' column of Table 1a. For ethanol-related scenarios, the results of the calculation show a mass flow rate with an oscillating behaviour over time and average values reported in the 'outflow' column of Table 1b.

The general perception of benchmarking participants with regard to the methodology, the format and assumptions made were very positive as shown in Fig. 4a.

More specifically, with reference to the sulphur-dioxide scenarios, the totality of the benchmarking participants considered that the *source terms*' calculations presented in the reference analysis were acceptable, whilst a lower consensus was reached for the ethanol-related scenarios (Fig. 4b). Some responses mentioned indeed a lack of clarity in the explanation of the behaviour of the outflow rate vs. time [10].

Some interesting observations were made with regard to the assumptions used for certain scenarios involving sulphur-dioxide, specifically, the duration of the release that is, the time elapsed from when the component failed until intervention by the operator. For

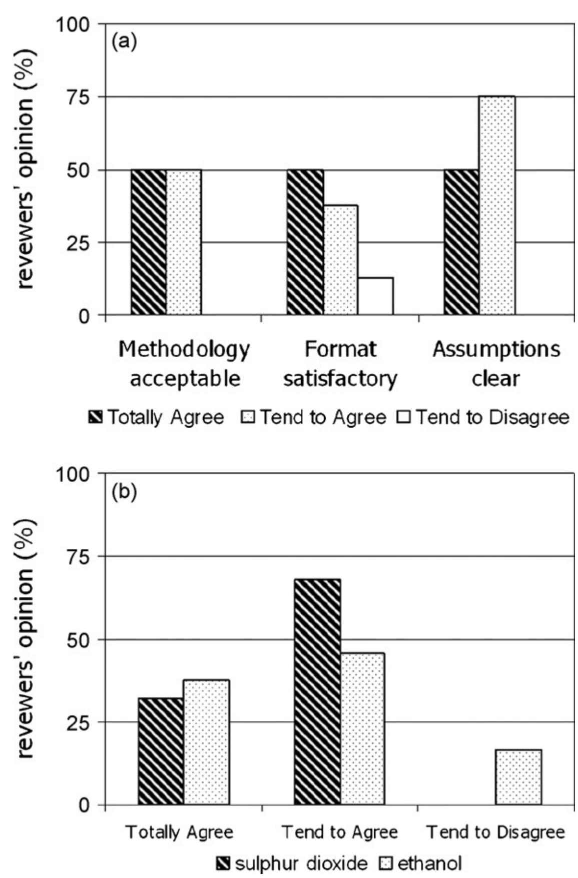

Fig. 4. General perception of the reviewers with regard to: (a) the methodology, the format and assumptions made, and (b) the results of source term calculations.

this reason, the benchmarking participants were asked about their perceptions regarding the proposed *reaction* and *repair* times. The *reaction time* of the operator, was assumed to be 20 and 30 min, for cases in which the gas detection sensors were present or not, respectively. The responses of the benchmarking participants were quite homogeneous in both cases with 50% of the responders preferring more conservative values (i.e., 30 and 40 min, respectively).

The *repair time* is particularly relevant for those scenarios that are associated with a non-isolatable release (i.e., TW151 and TW161). In such cases some additional time to repair the component failure is required. During this action the opening of the flange is necessary, an action that may produce an additional horizontal release of toxic gas. For this case the reference value assumed was 10 min. This value was considered to be too optimistic by the majority of responders (ca. 75%). Moreover, It was suggested that some specific sensitivity studies on this aspect should be conducted. It was also mentioned that different meteorological conditions could influence the repairing activity (e.g., rainy weather can transform the sulphur-dioxide into aerosols, thereby increasing the toxicity of the release).

3.4.2. Vulnerability models

In the study of consequence assessment, once the modelling of the accidents' effects (thermal radiation, overpressure wave, dispersion of toxic substances in the atmosphere) have been completed, the conversion of these results to the consequences is required. In order to estimate consequences of an accident on humans, a function relating the magnitude of the impact is required. This can be done by the so-called "vulnerability analysis". Usually, for quantitative risk assessment purposes, the method used to assess vulnerability is based on *Probit* functions. In other cases the analysis is concluded by the assessment of safety distances only. In these latter cases, the concentration field is compared to threshold limits (i.e., a limit on a measurable quantity representing a certain potential effect, established or formally accepted by a regulatory body).

Table 2 describes the alternative vulnerability parameters which were used in the benchmarking and which were reported within the questionnaire distributed to the reviewers. The data represented in bold were the data used in the reference risk assessment. The responses of the benchmarking participants, who were asked about their opinions in regard to the best choice amongst the proposed *Probit* formulas, is depicted in Fig. 5. In particular, Fig. 5a refers to *fire*- and *explosion*-related scenarios. For heat radiation (*fire*), a wide distribution of responses was noticed with the highest rating for TNO and DNV formulas. For overpressure-related scenarios (*explosion*), the probit formula of TNO was the definitive favourite. Fig. 5b refers to the toxic-related *Probit* formulas

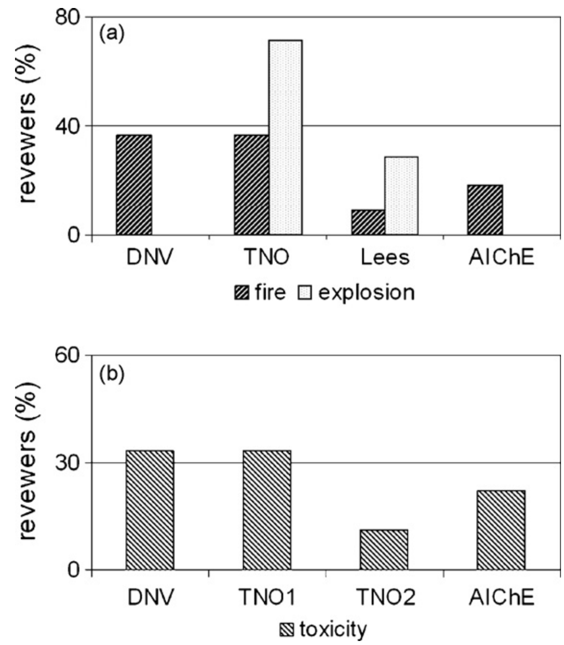

Fig. 5. Preferences of the reviewers regarding the probit model to be used: (a) fire and explosion, (b) toxics.

and shows the lack of any marked preference of the benchmarking responders amongst the different alternatives.

Concerning the threshold limits given in Table 2, there were differences in benchmarking participants' responses, many of whom also proposed some alternative values (i.e., 4.7, 5, and 3 kW/m^2 for fire, and 0.14 bars for overpressure). In particular, 1 bar was estimated to be the most appropriate value for the blast wave effect by the totality of responders, with the exception of one reviewer who proposed an alternative value of 0.14 bars. As expected, nobody was in favour of the higher values of Table 2 (2.4–3.1 bars). For toxics and fire effects, no specific preference was given for the different proposed values (i.e., toxic effects and fire) [10].

However, and regardless of the preferred values or formulas, it was commonly agreed that all the proposed values could be considered acceptable for safety report purposes. The discussions also acknowledged the ongoing difficulty of deciding which of the available formulas are the most reliable. For this reason, it was argued that a case-by-case approach should be followed for selecting the suitable model, influenced in particular by the type of potential impact predicted within each scenario and the underlying assumptions. However, it should be noticed that the choice of a specific

Table 2
Vulnerability data used for the benchmarking

Effect type	Probit estimation Probit equation (lethality)	Safety limit values Acceptable threshold values
Fire (heat radiation)	$-38.48 + 2.56 \cdot \ln(t[\mathrm{s}] \cdot Q^{4/3})$ [17] (DNV) $\mathbf{-14.9 + 2.56 \cdot \ln(\mathit{t}[s] \cdot \mathit{Q}^{4/3})}$ [19] **(Lees)** $-36.38 + 2.56 \cdot \ln(t[\mathrm{s}] \cdot Q^{4/3})$ [21] (TNO) $-39.83 + 3.0186 \cdot \ln(t[\mathrm{s}] \cdot Q^{4/3})$ [25] (AIChE)	2 kW/m^2 – 2nd degree burns in 20 s [18] 12.5 kW/m^2 – 2nd degree burns in 20 s [20] 35 kW/m^2 for 20 s – 50% fatality [22]
Explosion blast wave (overpressure)	$5–5{,}74 \cdot \ln(f(P[\mathrm{atm}], \mathrm{BW}))$ [21] (TNO) $\mathbf{-77.1 + 6.91 \cdot \ln(\mathit{P}[Pa])}$ [19] **(Lees)**	2.4–3.1 bar – 1% fatality [23] 1 bar–1% fatality [24]
SO_2 toxicity	$-16.89 + \ln(C^{2.4}[\mathrm{ppm}] \cdot t[\mathrm{min}])$ [17] (DNV) $\mathbf{-17.73 + 2.1 \cdot \ln(\mathit{C}[mg/m^3] \cdot \mathit{t}[min])}$ [21] **(TNO1)** $-27.9 + 1.14 \cdot \ln(C^{3.7}[\mathrm{mg/m^3}] \cdot t[\mathrm{min}])$ [21] (TNO_2) $-15.67 + 2.1 \cdot \ln(C[\mathrm{ppm}] \cdot t[\mathrm{min}])$ [25] (AIChE)	ERPG-2 IDLH

The data indicated in bold were those used as the reference for this exercise and used for the reference risk analysis. t = exposure time; Q = heat intensity [W/m^2]; P = peak overpressure; BW: body weight [kg]; C = toxic concentration.

formula is often driven by practical factors such as, for instance, its availability in the literature or open sources.

3.4.3. Other considerations

During the discussions following the review of the consequence assessment, it was confirmed that the main concerns of the competent authorities in EU-12 are more or less in line with those of the other EU countries. In particular, it became evident that no common methodology for consequence analysis is strictly required in the EU-12, and that they would gladly welcome further guidance in this area. Furthermore, it was argued that the competent authorities of the EU-12 are rarely in possession of the proper codes for performing modelling calculations for consequence assessment, and this is a further impediment to the competent authorities in effective implementation of their oversight responsibilities. For these reasons it was suggested that short-cut methods could be very useful for competent authorities in order to assess the consequence calculations in the safety report.

3.5. Risk assessment review

The final step of the benchmarking was to analyse the impact of the different reviews presented in the previous sections on the reference plant's risk estimate. The risk assessment was conducted by the JRC using the ARIPAR methodology. In particular, the reference data of the previous sections were used as the input data for ARIPAR, and the risk quantification procedure was carried out by aggregating all the risks associated to all the different hazardous sources and postulated scenarios. The outcome of this analysis was expressed in terms of *local risk* via risk contours and of *societal risk* via FN-curves. For reasons of space, this paper presents the result of the risk estimate in terms of the societal risk only. Complete information on the risk assessment calculations, that includes also the local risk maps, is reported elsewhere [10].

The impact of the different benchmarking participants' reviews on the overall estimate of risk was analysed by using new input data for ARIPAR (i.e., the revised values by the participants) and reassessing the overall risk. The result of such an analysis is depicted in Fig. 6, where the FN-curves obtained for each participant are compared with the FN-curve of the reference analysis (bold line). It can be noted that the spread of the results is rather significant both in terms of the absolute figure of risk and in terms of the shape of the FN-curves that is associated to the relevance of the different scenarios in contributing to the overall risk. From the results presented in the figure, it can be established that the risk estimates show quite clearly the strong influence of the differences of opinions amongst the benchmarking participants on the input data (i.e., frequency, and release times) and the probit models used. In general, the estimated risks are considerably higher than those presented in the reference risk assessment, which confirms the more conservative approach that is often typical of the authorities.

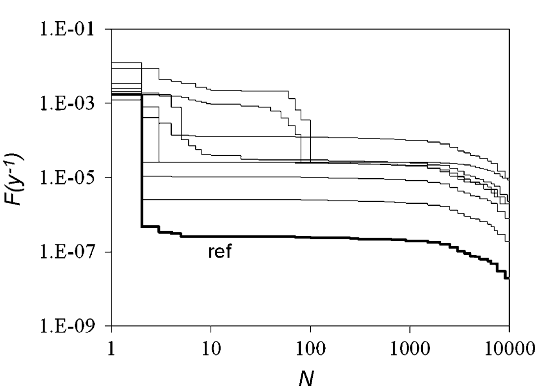

Fig. 6. Comparison of the FN-curve of the reference analysis (line in bold) with those calculated by using input data as reviewed by the benchmarking participants.

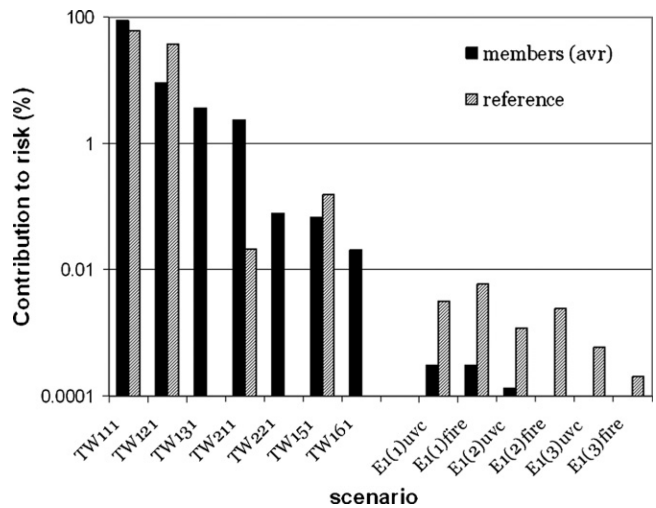

Fig. 7. Contribution to the overall risk estimate from the different accident scenarios. Black bars: average value for the benchmarking participants; striped bars: reference analysis.

Particularly interesting is the contribution of the different scenarios to the overall risk estimate. This is shown in Fig. 7, where the reference analysis is compared to the benchmarking participants' responses. More specifically, the bars with white stripes refer to the contribution to the risk estimate from each different scenario as obtained in the reference analysis. The same calculation has been conducted by averaging all the reviewed data of the benchmarking participants and re-processing the contribution to risk from each specific scenario. The result is represented by the black bars in the figure. From the general comparison, it can be seen that the participants' viewpoints also produced some marked differences from the reference analysis in regard to the way in which different scenarios influenced the final risk estimate. In both cases, scenarios TW111 (*catastrophic rupture of the TW*) and TW121 (*flange failure*) were considered by far the most significant. The largest difference was found for scenarios TW131 (*isolatable flexible pipe failure*) TW161 (*not isolatable flexible pipe failure*), and TW211 (*catastrophic rupture during TW change*), which were practically negligible in the reference analysis whilst some consideration has been given to them by the benchmarking participants. For ethanol-related scenarios, the risk estimate calculation of a potential pool fire or explosion, produced quite negligible results both in the reference analysis and in the benchmarking reviews (<0.01% of the overall risk).

Scenario TW121 (*flange failure*) prompted a rather heated debate within the benchmarking group. Despite the rather limited release associated with this scenario, the likelihood of occurrence is highest amongst all postulated scenarios. In addition, it was shown that scenario TW121 is quite sensitive to certain assumption and models used in terms of predicting consequences.

A comparison of the FN-curves from the reference analysis and those from the analysis conducted using the benchmarking participants' data is given in Fig. 8. This case shows a very large spread of responses. In this figure, the FN-curves produced from the conservative data suggested by the reviewers are indicated by the letters A and B. In these two cases, the selection of the model for assessing the vulnerability to sulphur oxide played the major role. In particular, curve A resulted from data suggested by the member who also favoured the most conservative probit model [25]. In contrast, curve B uses threshold limits, and gives more conservative results

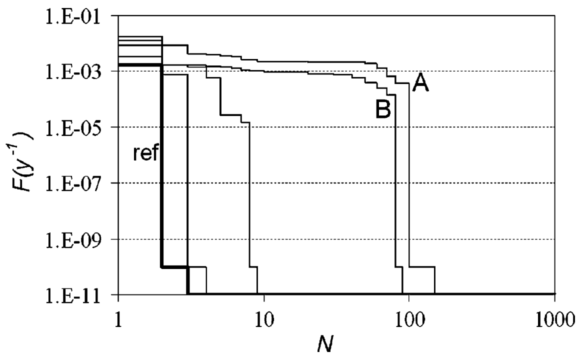

Fig. 8. Scenario TW121: comparison of the FN-curve of the reference analysis (line in bold) with those calculated using input data as revised by the benchmarking participants.

in comparison to the reference probit in the toxic concentration range of interest (i.e., 1–300 mg/m^3) [10].

The peculiarity of scenario TW121 in terms the uncertainty of its possible consequences, and in turn, of its potential for producing off-site risks, suggested further investigation of the scenario's sensitivities. Thus it was decided to perform a thorough analysis on the role played by certain assumptions necessary for the risk estimate. Assumptions for reaction and repair time were selected for the case involving a flange release, as they are directly associated with the amount of substance released to the environment. The response time consists of the time necessary to detect the release, to change into the proper protection equipment and to stop the release by closing the tank wagon valve, located on the top of the tank. The reference value, taken from the original safety report of the plant, was 20 min. For this exercise it was decided to run a risk estimate simulation for different (longer) values of the response time (i.e., 40, 60, and 120 min), representing situations in which the intervention of the operator is delayed or when such intervention may be impeded by unexpected conditions, which in turn might lead to a request for external intervention. The results of these calculations are shown in Fig. 9, which shows the how this assumption is critical.

As a final comment, it should be noted that the review of the risk assessment focused mainly on the influence of frequency data and vulnerability models. For this reason, the choice of these parameters was the subject of several discussions over the course of the project. Nonetheless, as shown in the above example, other assumptions also may play an important role in the overall risk assessment. Unfortunately, the significance of these aspects is not often immediately evident in the risk assessment process, and consequently they are not always examined with the appropriate level of scrutiny during the assessment or its subsequent review by the

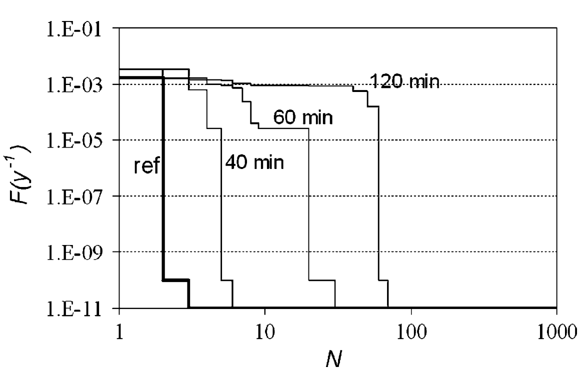

Fig. 9. Scenario TW121: comparison of the FN-curve of the reference analysis (line in bold) with those calculated by simulating different response times.

authorities. To illustrate, the assumption made with reference to the response time did not attract much attention during the review but the analysis of the final risk estimate clearly showed that the outcome is much more sensitive to this assumption than to other parameters.

4. Conclusions

The benchmarking presented in this paper is a first attempt to explore how independent reviews of the same risk assessment might differ in their findings and conclusions, and how these differences subsequently might have an impact of the area risk estimate. In this way this project differed significantly from the previous benchmarking exercises involving major accident hazards that focused on the independent execution of a risk assessment, conducted on the same reference establishment. The difference was not only associated with the purpose of the benchmarking (i.e., risk assessment evaluation rather than execution), but also with the fact that the benchmarking was conducted from a completely different perspective (i.e., regulatory authority rather than operator). Nevertheless, and despite of these differences, a comparison of the main results of this benchmarking with those of the previous exercises reveals several commonalities. In particular, participant opinions varied widely and marked all different phases of the risk assessment process. In the previous exercises, the wide variety of opinions was clearly linked to the intrinsic uncertainty of the risk assessment process.

Risk assessment is indeed a very complex process, characterised by the presence of significant and irreducible uncertainties. In addition as for any other complex process, the "multiplicity of different legitimate perspectives" (national, situational, etc.) is also responsible for different results [26]. For instance, it is rather logical that, regardless of the spread of opinions amongst the different participants, there was a general tendency toward higher figures of risk as compared to the reference analysis. Notably, the evaluation of the risk assessment was conducted from a regulatory perspective that inherently tends to be more conservative, due to the nature of its responsibilities (ensuring the public good). This factor represents a further example of the complexity associated with the process of elaborating evaluating, and endorsing a risk assessment for safety report purposes, because it is a process that necessitates the involvement of actors with different perspectives, in particular, the establishment's operator and the regulatory authorities. The process of finding or creating consensus around key inputs is ongoing and arduous, but essential for reaching agreement, or at least acquiescence, in the final evaluation of the risk. A common or accepted view can only be achieved through a transparent process aimed to reach consensus between the regulator and the operator, in which the operator presents the risk assessment to the operator, followed by an open dialogue between the two on its contents and interpretation. In this context, the implementation of a common format to exchange risk assessment data and information could be very valuable and helpful to facilitate the dialog and accelerate the consensus building. In the current situation, the authority is indeed obliged either to perform the verification by means of the same tools used by the operator, or to develop an ad hoc-conversion module to import, in its own tools, the model and the data to be verified. The existence of a standard representation of the plant safety model would allow a regulatory authority to import models generated by any modelling tool without having to manage as many conversion modules as the number of different tools.

Moreover, with reference to the present benchmarking, the following specific observations are also relevant for operators and authorities alike:

- In some situations worst case scenarios may have received too much scrutiny in proportion to their likelihood. The comparison between TW111 and TW121 is a good illustration of this problem.
- A very large spread of opinions was found for frequency data. The reviewers quoted several sources of data to justify their choices and, in some cases, the applied expert judgment. A point to note is that several scenarios were driven by human factors-related events, which were considered to be much more difficult to assess. These scenarios are indeed dependent on a combination of factors (procedures, safety culture, etc.) that are company/plant specific and their evaluation is very difficult from a regulatory perspective. Human factor analysis is, therefore, an essential element and should be incorporated into any risk assessment study for Seveso purposes.
- The presence of different vulnerability models for consequence assessment (probit models) is very crucial for the risk estimate. For some hazardous substances there are several models available in the literature, and in some cases they differ significantly with each other. The inherent difficulty associated with the validation of these models makes the model choice one of the main contributors to the uncertainty of the final results. Any conclusion or recommendation to address this problem?
- Underlying assumptions, which are made in the different phases of the risk assessment process, can play a substantial role in the final risk estimate (e.g., the response times, in the present exercise). However, the greatest attention is normally given to other aspects such as, for instance, the frequency data and the damage curve calculations by neglecting the important of certain assumptions, which are taken from granted. Equal, or even greater attention, should also be given to questioning underlying assumptions that drive the selection of important parameters (e.g., duration of release).
- Due to the intrinsic uncertainty associated with the risk assessment, the absolute value of the risk estimate is not necessarily the most important outcome of the overall process. Rather, the QRA framework necessitates a detailed analysis of the risk situation, which leads to a better understanding of the systems and processes involved and highlights which are the critical elements.
- It should be noted that for very complex installations a full QRA could be very difficult to evaluate. The amount of information required can be significant and the corresponding uncertainty associated with each parameter may, therefore, also be very difficult to estimate. Detailed guidance on how to evaluate a risk assessment from a regulator's standpoint would be extremely useful for the new Member States and Candidate Countries.

Finally all the participants recognised that the benchmarking study was an effective mechanism for identifying the strengths and weaknesses within their own country's strategy for reviewing the risk analyses of safety reports. The study created an active discussion platform, focusing on current practices and approaches used by the participating countries for analysing risk associated with Seveso-type establishments. Additionally, this approach allowed a productive exchange of information to take place amongst the participants on several aspects concerning the implementation of the Seveso Directive in their countries. In particular, this information exchange was highly valued by the study members given the recent entrance into force of the Directive in the new Member States and Candidate Countries.

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Appendix A. Participating organisations

The participants in this benchmarking study consisted of representatives of competent authorities from newly acceded Member States within the EU with responsibilities associated to the implementation of the Seveso Directive in their countries. Risk analysis experts working in research organisations were also represented. The JRC has covered the travel and subsistence expenses for all invited experts in accordance with European Commission rules whist the experts provided their contribution in kind for all those activities related to the review of the risk analysis of the reference establishment. The list of the invited experts with their affiliations is given hereunder:

Bulgaria
Tconka Dryankova, Ministry of Environment and Water.

Cyprus
Themistoclis Kyriacou, Department of Labour Inspection.

Hungary
Sándor Czakó, CK-Trikolor
Lajos Kátai-Urbán/Zoltan Czeplo, National Directorate General for Disaster Management – Ministry of the Interior.

Latvia
Maigurs Ludbarzs, Strategy Division of Civil Protection Department.

Lithuania
Vytis Kopustinskas, Lithuanian Energy Institute.
Petras Voveris/Ausra Sablinskiene, Fire and rescue Department, Ministry of the Interior.

Poland
Adam Markowski, Technical University of Lodz.
Andrzej Furtek, Centre of excellence MANHAZ (Management of Health and Environmental Hazards).

Romania
Alxandru Ozunu/Septimius Mara, University of Cluj-Napoca.

Slovenia
Jasmina Kasba, Ministry of Environment, Spatial Planning and Energy.
Jernej Per, Slovenian Environmental Agency-EIA Department.

Slovakia
Magita Galkova, Environmental Agency.

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