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Reference criteria for the identification of accident scenarios in the framework of land use planning

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ABSTRACT

Land use planning (LUP) around industrial sites at risk of major accidents requires the application of sound approaches in the selection of credible accident scenarios. In fact, the 'technical' phase of LUP is based on the identification and assessment of relevant accident scenarios. An improper choice of scenarios may critically affect both the 'technical' phase of risk assessment and the following 'policy' phase concerning decision making on land-use restrictions and/or licensing. The present study introduces a procedure aimed at the systematic identification of reference accident scenarios to be used in the gathering of technical data on potential major accidents, which is a necessary step for LUP around Seveso sites. Possible accident scenarios are generated by an improved version of the MIMAH methodology (Methodology for the Identification of Major Accident Hazards). The accident scenarios are then assessed for LUP relevance considering severity, frequency and time scale criteria. The influence of prevention and mitigation barriers is also taken into account. Two applications are used to demonstrate the proposed procedure. In both case-studies, the proposed methodology proved successful in producing consistent sets of reference scenarios.

1. Introduction

Major accidents in industrial facilities may trigger severe off-site consequences. The large number of off-site casualties which occurred following the San Juan Mexico City (Mexico, 1984) and Bhopal (India, 1984) disasters provided compelling evidence that adequate separation distances should be maintained between hazardous facilities and densely populated areas. Moreover, the events of Enschede (Netherlands, 2000) and Toulouse (France, 2001) evidenced that separation distances can slowly be eroded over time, resulting in hazardous facilities being encroached by urban development. The prime goal of an effective land use planning (LUP) policy around major accident hazard sites is protecting the population from the consequences of severe outcomes and establishing adequate minimal safety distances that define the areas where land use restrictions need to be maintained. The European Union (EU) Directive 96/82/EC (Seveso-II Directive) addresses two key aspects of LUP: separation between hazardous installations and residential and other sensitive areas (i.e. safety distance) and the systematic technical framework for its assessment and scrutiny. However, the Directive itself does not provide any detailed guidance on how LUP regulations should be implemented by the EU Member States (MS) into their National LUP policies, since besides the technical elements a number of other aspects need to be considered (technological, social, cultural and economic, etc.) (Tugnoli, Santarelli, & Cozzani, 2011).

LUP activities include a "technical" phase (identification of scenarios, assessment of consequences, etc.) and a "policy" phase (acceptability criteria, zoning, permits, etc.). While the second one may be strongly influenced by country specific factors, a general rule that defines appropriate safety distances is currently unavailable, even when considering only the merely technical point of view. Several EU MS (e.g. Netherlands, United Kingdom and France) have developed and implemented specific methodologies, regulations and policies (Christou, Amendola, & Smeder, 1999; Christou, Gyenes, & Struckl, 2011). For instance, the PHADI methodology for land use planning advice in United Kingdom (HSE, 2011) and the implementation of the ELECTRE III multi-criteria ranking in hazard zoning in France (Salvi, Merad, & Rodrigues, 2005) are among the more recently proposed technical tools for supporting LUP decisions around major hazard installations.

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Apart from the inevitable differences in methods and criteria (both inside and outside the EU), any LUP approach actually has the same starting point: a technical evaluation of the risks of credible major accident scenarios considered for a given site of interest. Such a technical basis, which should be obtained by a transparent, consistent and assessed methodology, is necessary for any sound LUP and licensing negotiation or decision process.

Due to the large number of factors involved (hazardous substances properties, processes, presence of safety barriers, etc.), a very large number of potential accident scenarios can be generated during a hazard identification process. Hence a prioritization procedure is required to make the accident scenario analysis practicable and justified in terms of human resources, time and costs. Thus, the major difficulty to overcome is identifying the credible accident scenarios among the possible ones. Such identification procedure must guarantee that the identified accident scenarios are consistent among all major hazard plants. This is a critical aspect, as the evaluation of appropriate safety distances strongly depends upon the accident scenario considered. Several previous benchmark studies have shown how the set of accident scenarios considered has a strong impact on the final results of a hazard analysis or risk assessment. This may lead to a considerable reduction in the effectiveness of LUP and population protection (Christou et al., 2001, 2011; Cozzani, Bandini, Basta, & Christou, 2006; Delvosalle et al., 2005; Pey, Lerena, Suter, & Campos, 2009).

The present study proposes a systematic procedure to generate reference accident scenarios necessary to build the technical basis of LUP decision-making. The procedure therefore may constitute a preliminary screening step, providing an input to other technical tools used in the decision phase of LUP: e.g. PHADI (HSE, 2011), ELECTRE III-based hazard zoning (Salvi et al., 2005), and RISKCURVES (Van Het Veld, Boot, & Kootstra, 2007). As a starting point, accident scenario identification is based on an extended version of the MIMAH methodology (Methodology for the Identification of Major Accident Hazards), developed within the FP6 EU project ARAMIS (Delvosalle, Fievez, Pipart, & Debray, 2006). A new systematic two-stage validation procedure is then introduced to work out a table of relevant scenarios. The first stage of the validation procedure provides practical guidelines on the integration of the draft table of scenarios with the results from the screening of past accidents and from a simplified HazOp assessment. In the second stage of the validation, decision criteria are introduced to select the relevant scenarios on the basis of four driving issues: (a) frequency, (b) severity, (c) presence and effectiveness of safety barriers, as implemented by good practice, and (d) time scale of the scenario (i.e. time of evolution of the scenario, which affects the possibility to mitigate off-site consequences).

Two applications of the procedure are presented. The first case-study analyses a matrix of five generic reference installations and 12 hazardous substances. From this pre-screening, reference accident scenarios are identified and they can be further used to populate a knowledge system for supporting a more consistent LUP assessment practice across the EU. The second case-study concerns the specific assessment of a LNG regasification terminal.

2. Methodology

The proposed procedure in the present study aims at the identification of the accident scenarios which can be relevant for LUP purposes around major hazard establishments classified as Seveso sites, independently of specific risk-based or consequence-based approaches later adopted in the decisional phase of LUP (Cozzani et al., 2006). The proposed procedure can be applied to both existing and new plants and requires the typical input information needed for risk assessment studies (CCPS, 2000; Mannan, 2005; Uijt de Haag & Ale, 2005). In the present framework, an accident scenario contains the event sequence starting from an unwanted Loss of Containment (LOC) event and ending with a final dangerous phenomenon (e.g. an explosion, a pool fire, etc.) (Christou, Struckl, & Biermann, 2006).

To this purpose an improved version of the MIMAH methodology was developed for identifying possible accident scenarios. MIMAH is a step-by-step methodology for the identification of accident scenarios, which is carried out with the development of generic fault and event trees. The methodology is based on a taxonomy of equipment and of properties of the hazardous substances, and includes a database of reference fault and event trees (Delvosalle, Fievez, & Pipart, 2004). The use of the MIMAH approach can be justified as being reasonably representative of the current state-of-the-art in accident scenarios identification, since it was originally developed within the EU FP6 ARAMIS project (Delvosalle et al., 2006).

A two-stage systematic procedure is then applied to the draft table of potential accident scenarios obtained by MIMAH to work out the relevant scenarios that should be reasonably considered for LUP. In the first stage, the draft table is revised and integrated with the results obtained from a layered approach based on specific identification techniques. In the second validation stage, practical rules are provided to select the accident scenarios relevant in the LUP context from the general list obtained in stage I. An outline of the main steps of the method is shown on Fig. 1. The figure demonstrates the linear step-by-step structure of the method. Table 1 presents in detail the correlation between the proposed method and the original steps of the MIMAH procedure.

2.1. Identification of accident scenarios

The first step of the proposed procedure generates a draft list of critical events for each of the hazardous equipment present in the plant. Even though all of the relevant steps of the MIMAH procedure are adopted (see Table 1), the practical application of the original version of the method requires a few integrative actions to overcome some of its limitations (see e.g. the reference customization criteria reported in Table 3).

Step 1 of the original MIMAH calls for the collection of the information needed for the assessment (general data about the plant, description of processes, description of equipment and pipes, substances stored or handled and their hazardous properties). Given the context of a LUP assessment this information should be readily available (e.g. from the plant safety report).

Using the information collected, substances and equipment are classified according to a pre-defined taxonomy (step 2 of original MIMAH). The classes in the original MIMAH procedure (Table 2) did not provide an explicit classification of some categories of hazardous equipment (e.g. gasometers and truck loading/unloading facilities). A general rule was proposed to bridge this gap: the unclassified equipment items are assigned to the most appropriate MIMAH equipment (EQ) class on the basis of geometrical and functional similarities (Table 3).

The original MIMAH contains a step devoted to the selection of the hazardous equipment (step 3). This is based on an indexing approach, where the mass of hazardous material is compared to a threshold quantity. Since the current procedure is applied in the context of a LUP assessment, this step is not necessary (Table 1), as critical equipment items should have been already identified.

Loss of Containment (LOC) events, also called critical events (CE), are associated with the equipment using the reference tables of the original MIMAH procedure, which accounts for the

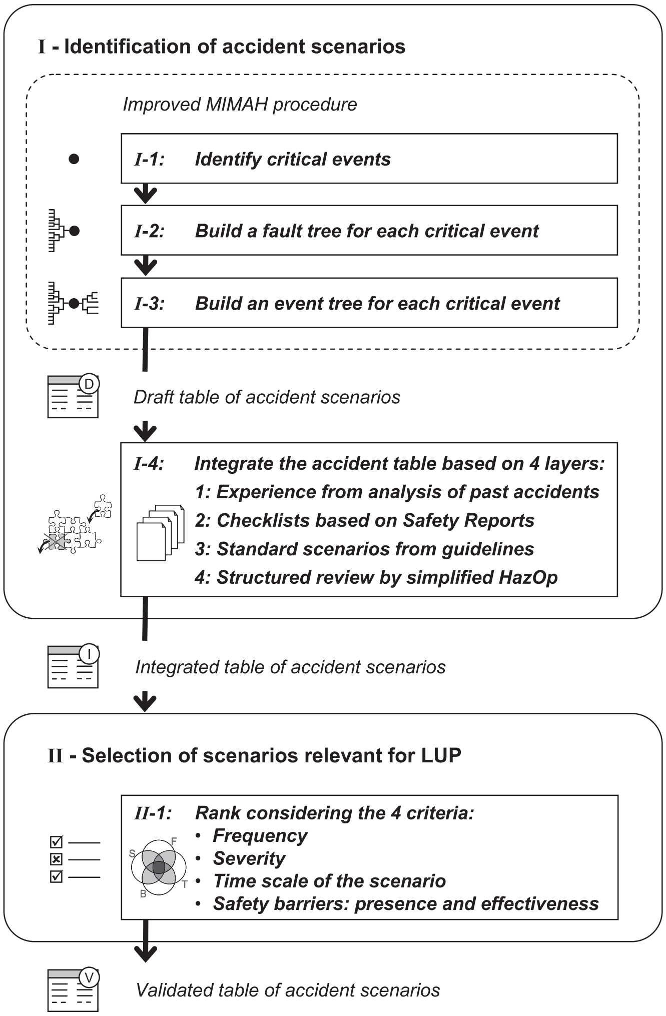

Fig. 1. Flow chart of the proposed procedure.

Table 1
Comparison between MIMAH (Delvosalle et al., 2006) and the proposed procedure.

Step in the original MIMAH	Step in the proposed procedure	Comment
Step 1: Collect needed information	Not present	Current procedure is applied in the context of a LUP assessment. Availability of information is implicit.
Step 2: Identify potentially hazardous equipment in the plant	Step I-1: Identify critical events (CE)	Classification of hazardous equipment (EQ) is adopted from MIMAH. It is at the basis of identification of critical events (CE) in the current procedure.
Step 3: Select relevant hazardous equipment (EQ)	Not present	Current procedure is applied in the context of a LUP assessment. Hazardous units are already identified.
Step 4: For each EQ associate critical events (CE)	Step I-1: Identify critical events (CE)	Heuristic rules for identification of critical events (CE) are adopted from MIMAH.
Step 5: For each CE build fault trees	Step I-2: For each CE build a fault tree	This step is adopted from MIMAH.
Step 6: For each CE build event trees	Step I-3: For each CE build an event tree	This step is adopted from MIMAH.
Step 7: For each EQ build all the complete bow-ties	Not present	This step is not explicit in current procedure; it can be intended as direct result of steps I-2 and I-3.
Not present	Step I-4: Integration of accident table	A systematic four-layer procedure is developed for the integration of the draft table of accident scenarios.
Not present	Stage II: Selection of LUP-relevant scenarios	Practical rules are provided to select LUP relevant scenarios with respect to frequency, severity, safety barriers and time evolution.

equipment class and physical state of the substance contained (Delvosalle et al., 2006). Table 2 lists the CE classes considered in the MIMAH procedure. Hence, MIMAH provides a set of generic fault trees that can be easily associated to each CE, thereby yielding a preliminary list of causes and accident chains (Delvosalle et al., 2004). However, the MIMAH procedure does not provide criteria to customize generic fault trees on a case by case basis. A preliminary customization can be based on a set of heuristic criteria proposed in Table 3. This preliminary screening may remove some of the branches or LOCs from the fault trees rather than adding new ones. As a matter of fact, adding new branches in the event tree requires a structured approach in order to yield consistent results, and will be the object of a specific validation step described later on (see step I-4).

Event trees are built for each equipment item following an approach based on the generic event trees in the MIMAH procedure. The event trees link each identified CE to the possible final dangerous phenomena. Similarly to fault tree definition, heuristic criteria for a preliminary adaptation of the generic trees to the specific characteristics of the unit and to the properties of the contained material are also proposed (Table 3).

Altogether, the identification stage takes advantage of the modular structure of the MIMAH approach, making the development of the draft table of scenarios relatively swift in terms of time and human resources.

2.2. Integration of accident scenario draft table

The preliminary list of accident scenarios and the corresponding bow-tie diagrams (i.e. event and fault trees) obtained by the improved MIMAH need to be validated and integrated by a specific and systematic procedure not provided by MIMAH. The following four-layer procedure is applied for the validation and integration of the draft accident table, based on the approach proposed by ISO 17776 to hazard identification (ISO, 2000):

- *Layer 1: Experience derived from analysis of past accident databases*. The main major accident databases (MHIDAS, eMARS, ARIA, etc.) are searched to recover data about accidents involving the addressed substance/reference installation. Though most accident records usually do not provide sufficiently detailed information to characterize the release event, the dangerous phenomena and the causes or relevant clusters of causes can be identified. This technique is particularly suitable for units with a consolidated technology and operative experience.
- *Layer 2: Checklists based on relevant Safety Reports*. The availability of accessible Safety Reports for similar Seveso installations can provide a checklist of the failure modes, final scenarios and primary causes for equipment items and operations. However, the application of the technique, while building on recognized hazards previously addressed in consolidated assessments, is limited by the accessibility of relevant

Table 2
List of equipment classes (EQ) and critical events (CE) considered in the original MIMAH procedure (adapted from Delvosalle et al., 2006).

ID	Full name
Equipment classes	
EQ1	Mass solid storage
EQ2	Storage of solid in small packages
EQ3	Storage of fluid in small packages
EQ4	Pressure storage
EQ5	Padded storage
EQ6	Atmospheric storage
EQ7	Cryogenic storage
EQ8	Pressure transport equipment
EQ9	Atmospheric transport equipment
EQ10	Pipes networks
EQ11	Intermediate storage equipment integrated into the process
EQ12	Equipment devoted to the physical or chemical separation of substances
EQ13	Equipment involving chemical reactions
EQ14	Equipment designed for energy production and supply
EQ15	Packaging equipment
EQ16	Other facilities
Critical event classes	
CE1	Decomposition
CE2	Explosion
CE3	Materials set in motion (entrainment by air)
CE4	Materials set in motion (entrainment by a liquid)
CE5	Start of fire (loss of physical integrity, LPI)
CE6	Breach on the shell in vapour phase
CE7	Breach on the shell in liquid phase
CE8	Leak from liquid pipe
CE9	Leak from gas pipe
CE10	Catastrophic rupture
CE11	Vessel collapse
CE12	Collapse of the roof

data. Site-specific factors must be carefully evaluated when using this approach.

- *Layer 3: Analysis of standard scenarios proposed by guidelines.* Relevant technical and normative guideline documents are consulted in this layer in order to verify that the preliminary list of accident scenarios is complete and sufficiently representative and/or to assess whether integrations are needed to meet the common practice standard. Examples of such guidelines are the API standard 581 (API, 2000), ISO 17776 (ISO, 2000), EN 1473 (CEN, 2007), NFPA 59 (NFPA, 2001), etc.
- *Layer 4: Structured review approach based on a simplified Hazard and Operability Analysis.* A HazOp analysis of a reference scheme of the installation is performed. The simplified HazOp screening provides information about (i) top-events that should be considered for reference accident scenarios definition; (ii) failure chains leading to the top-events; and (iii) clusters of causes leading to the top-events. This technique is more onerous in terms of complexity and resources. Therefore, it should be applied to innovative technologies or to assessments that require a thorough consideration of site-specific and equipment-specific features that are not adequately addressed at the lower layers.

Clearly enough, the application of the above integration procedure in practical cases should be carefully considered. Each layer contains a technique based on a different level of complexity and, thus, of expertise, resources, and time required for its application (CCPS, 2008; Mannan, 2005). Integrating information from independent studies throughout the lifecycle of the project is the key strategy in order to limit the time and resource burden of the assessment and meet the typical time frame of hazard identification techniques.

In the specific context of the identification of LUP candidate scenarios, the procedure may be limited to the application of the lower layers: e.g. on one hand, for consolidated and widely applied technologies, the experience collected in past accident databases (Layer 1) may be sufficient to provide a sound validation of the candidate LUP scenarios obtained from the extended MIMAH application. On the other hand, the application of all the four layers should allow a systematic cross-validation of results, providing a complete list of potential scenarios candidate for LUP assessment. In particular this will prevent the exclusion of low-frequency high-severity scenarios, which may occur with an inaccurate application of single hazard identification techniques (Paltrinieri, Dechy, Salzano, Wardman, & Cozzani, 2012).

Table 3
Reference customization criteria introduced for the identification of accident scenarios.

Step – Task	Criteria	Example
I-1: Identify critical events – Identify hazardous equipment category (EQ)	For equipment not included in original EQ classes of MIMAH, select the more appropriate MIMAH EQ based on geometrical and functional similarities	Loading/unloading facilities, hoses and connection arms are considered within geometrical class "EQ10 – pipe network"
I-2: Build a fault tree – Customize the generic tree	Exclude causes not applicable due to material properties	For non flammable/reactive materials do not consider causes like "internal combustion/explosion"
	Exclude causes not applicable due to equipment characteristics	Causes as "leak/rupture of internal high pressure source" are excluded when utilities such as high pressure steam coils are not present
	Exclude causes not applicable due to operation characteristics	Scenarios as "filled beyond normal level" are not considered if inventory material is in gas/vapour state
I-3: Build an event tree – Customize the generic tree	Exclude events not relevant due to properties of the contained material	Eliminate fire scenarios for non-flammable materials
	Propose conditional exclusions depending upon the verification of specific additional information	Check if initial concentration and temperature of a water–ammonia pool may yield toxic concentrations in air
	Mark with warning notes the specific scenarios that may occur only under particular enabling conditions	Only the release of LNG over water can give raise to a Rapid Phase Transition scenario

The list of critical events and final scenarios identified by the above techniques and the draft table from step 1 (see Section 2.1) should then be integrated to obtain a consistent and complete list of candidate scenarios.

Particular attention should be devoted in this phase to the inclusion of scenarios involving multiple units of equipment in the validated list. The fault trees developed from the preliminary MIMAH approach already include some common causes (natural hazard, domino effects, etc.) for single equipment units. However in the validation phase, the possible occurrence of combined multiple scenarios should be recognized by the multi-layer approach and be proposed as an independent accident scenario for LUP.

2.3. Selection criteria for the scenarios relevant for LUP

The integrated list of accident scenarios obtained from the above procedure should include all of the credible scenarios that can originate from each plant unit. However, not all of the accident scenarios may be of interest for LUP purposes. Only accident scenarios that have potential off-site consequences should be considered. Being able to eliminate the unnecessary ones will greatly reduce the effort needed for the following phases of consequence assessment. It is worth noting that the number of scenarios that will pass this selection phase is strongly dependent on the characteristics of the accident scenarios (properties of the substances, characteristics of the equipment, frequency of initiating causes, etc.), and may range as well from none to all of the accident scenarios in the initial list.

The accident scenarios with potential off-site consequences can only be identified when information is available about the specific plant lay-out and substance inventory, and only if the consequences of related dangerous phenomena have been assessed. The potential off-site consequences usually can not be assessed *a priori* by a conservative approach. Practical rules based on a semi-quantitative consultation matrix were developed therefore to prioritize the criticality of accident scenarios (Table 4). The matrix identifies three relevance categories for LUP on the basis of four key parameters: (1) frequency, (2) severity, (3) time scale of the scenario and (4) presence and effectiveness of safety barriers. These parameters are defined in the guidelines on LUP issued by the EC Major Accident Hazards Bureau (Christou et al., 2006). The consultation matrix applies to the LOC events and to all of the dangerous phenomena associated to an accident scenario. The most conservative category associated to the accident scenario is the one deriving from the application of the first three criteria. If safety barriers are present then the accident scenario category should be revised accordingly to the safety barriers considered. The consultation matrix proposed in Table 4 can be easily modified to account for specific LUP criteria and/or for site-specific data, which may allow the use of less conservative exclusion criteria.

2.3.1. Frequency

In the present context, the expected accident scenario frequency is used exclusively as an indicator for the accident scenario criticality. It should be noted that several EU LUP approaches do not accept expected accident scenario frequency as an actual cut-off criterion. In this study a 10^{-6} events/year threshold value is proposed as a limit criteria, above which the scenario can not be neglected for LUP purposes (**type a**). The value is based on a conservative analogy with individual risk acceptability thresholds (Ale, 2002; Christou et al., 1999; Mannan, 2005; Starr, 1969). It may be remarked that the current practice in some countries (e.g. Italy) is to neglect the accident scenarios having expected frequencies lower than $10^{-8} \div 10^{-6}$ events/year. Therefore scenarios having frequencies lower than 10^{-6} events/year may be generally considered for exclusion depending on the specific LUP criteria (**type b**). A survey of past accidents associated to the installation and to the material of concern can provide a short-cut appraisal of the frequency criterion: if more than 2% (or at least 2) of the past accidents have involved a given LOC, then the accident scenario should be reasonably included in **type a**. The given arbitrary threshold is chosen in order to promote inclusion in LUP analysis of all the scenarios that actually occurred more than once. Scenarios with lower occurrence should be investigated on a case by case basis (**type b**).

2.3.2. Severity

Accident scenarios having only “short-range” consequences, without triggering domino effects, can be disregarded for LUP purposes. Despite technical literature reporting that jet fires, pool fires and confined explosions are likely to have only local consequences (Cozzani, Tugnoli, & Salzano, 2009; Mannan, 2005), *a priori* exclusion seems non-conservative. Hence severity ranking of the accident scenarios considers only **type a)** and **b)** classes. The class is assigned according to the typical spatial scale of effects from the dangerous phenomena (Table 4).

2.3.3. Time scales and delays

The time scale of the accident scenario reflects the time available to activate and implement measures for mitigating off-site consequences as far as (reasonably) possible. Three factors mainly define the time scale of a scenario: (i) source term; (ii) ignition and ignition delay; (iii) time evolution of the dangerous phenomenon. However not all these factors can be effectively used to discriminate the relevance of accident scenarios for LUP purposes.

The time scale component related to the source term depends upon the intensity of the LOC. Typical “large” release rates occurring in very short time periods are likely to lead to off-site consequences, requiring the accident scenario to be considered for LUP. The release intensity also depends on the released substance as well as other factors which are difficult to assess *a priori*.

The possibility of ignition delay can not be effectively used to exclude accident scenarios, since the actual value of the delay is not easy to predict. Nevertheless, possible roles of active protection may be accounted for.

Dangerous phenomena such as fireballs and confined explosions have a time scale of order of seconds, thereby making any mitigation action virtually impossible. Pool fires and jet fires do have a significant time duration, thus enabling to prevent off-site consequences both through mitigation as well as protection actions (Gomez-Mares, Tugnoli, Landucci, & Cozzani, 2012). If the accident scenario involves dispersion, the time-lapse available for mitigation measures is again dependent on the source term: the formation of cloud in catastrophic or large continuous releases is almost instantaneous and using water curtains may represent the only possible mitigation; on the other hand, low-intensity continuous releases are typically the case, where the risk reduction impact of mitigation systems (e.g. shut-down systems) or protection barriers can be remarkable. Table 5 summarizes these considerations noted above and links each dangerous phenomenon to

Table 4
Consultation matrix for exclusion criteria.

Accident scenarios	Type a) scenarios: Should be considered for LUP	Type b) scenarios: May be considered for LUP depending on the specific LUP criterion adopted	Type c) scenarios: May reasonably not be considered for LUP
Frequency	$\geq 10^{-6}$ events/year	$<10^{-6}$ events/year	–
	≥2% and ≥2 past accident scenarios reported	<2% and <2 past accident scenarios reported	–
Severity	Possible DP include: fireball, VCE, flash-fire, toxic dispersion	Possible DP only include: jet fire, pool fire, confined explosion	–
Time scale	Possible DP include (Table 5): 1, 2, 5a, 6a, 7a	Possible DP include (Table 5): 3a, 4a, 5b, 6b, 7b	Possible DP only include (Table 5): 3b, 4b
Safety barriers	Procedural, active or no barriers	Passive barriers	Inherent barriers

DP: dangerous phenomena.

a class of relevance for LUP with reference to the time scale criteria. Two tiers of intensity of loss of containment are considered for some scenarios. The table also suggests applicable mitigation and protection barriers for each dangerous phenomenon.

2.3.4. Safety barriers

The presence of safety barriers can make some scenarios irrelevant for LUP purposes; this is possible for both prevention barriers (e.g. pressure relief devices, fault-safe systems, vacuum design) and mitigation barriers (e.g. catch basins, shut down, blow down). The effectiveness of such safety barriers, however, may be different, depending upon the context and the specific national regulations or control authorities. A conceptual hierarchy of barriers exists: inherent, passive, active and procedural (Bollinger et al., 1996). Procedural and active safety barriers do not significantly influence the relevance of a scenario for LUP (**type a**), since these barriers can not prevent the scenario from occurring, but solely reduce its frequency (Kletz & Amyotte, 2010). On the other hand, passive barriers may lead to the exclusion of a scenario, depending on the adopted LUP criterion (**type b**). Inherent safety barriers reasonably enable the exclusion of a scenario as well (Tugnoli, Landucci, Salzano, & Cozzani, 2012), independently of any other criteria (**type c**).

3. Case-studies

The procedure described above was applied to a matrix of several substance-installation pairs. The first case study presented here demonstrates how the methodology can generate a validated list of accident scenarios for a set of typical installations across the EU. The second case study applies the proposed method to a specific installation: an on-shore liquefied natural gas (LNG) regasification terminal.

3.1. Case-study 1 – generic reference installations

Twelve hazardous substances among the most commonly handled in Europe are selected for the case study. Five installations in Seveso plants are then selected, involving the most common operations of these twelve identified materials (storage, loading/unloading, pipe transfer, etc.). Afterwards, couples are formed between the installations and the twelve substances, as shown in Table 6. Combinations that are impossible because of the physical nature of the substance (e.g. storage of liquid LPG at ambient conditions) or that are not relevant within the current industrial practice (e.g. large scale cryogenic storage of hydrogen sulphide) were excluded (Kirk & Othmer, 2007; Ullmann, 2008). Table 6 also highlights that different physical states are possible for the same substance and the same installation (e.g. pipework).

A reference installation was defined for each substance/installation couple. For each one, a typical process flow diagram is proposed. The diagram accounts for design, operation and safety issues typically required for the substance(s) handled. An example detailing a typical process flow diagram is shown in Fig. 2, featuring a cone roof tank for the storage of flammable liquids and the connected auxiliary equipment, controls and safety devices.

A preliminary list of critical events and bow-ties is obtained from the application of the relevant steps in the MIMAH procedure described in Section 2. In a few cases only, the definition of critical events required the introduction of assumptions concerning geometrical and functional similarities (e.g. variable volume atmospheric storage tanks are accounted for as pressure storage of gas, loading/unloading facilities for the liquids considered could be captured with the bow-tie for the corresponding transport equipment and pipework, etc.). A few critical events were eliminated during the customization of the trees, as well as several causes (e.g. “Leak from gas pipe (CE9)” in the specific case of a “Pipe network (EQ10)” installation containing a pressure liquefied gas or a cryogenic liquid).

The above described procedure leads to the definition of generic bow-ties. These are used to develop more detailed and specific bow-ties in the integration and validation phase (step I-4). The use of structured methods (e.g. HazOp) and past accident analysis is crucial. Fig. 3 illustrates an example of the fault tree integration process. The section of the tree in the figure concerns some causes of internal overpressure. The causes which were not credible for the system under assessment (cryogenic storage of LNG) were identified in the standard tree of MIMAH (shaded in Fig. 3-a), and eliminated following the heuristic criterion of Table 3 (e.g. runaway reaction is not credible for LNG). The tree was then integrated with the results from the HazOp assessment (shaded causes in Fig. 3-b), producing a validated tree branch.

Table 5
Relevance of scenarios for LUP based on time-scale factors.

Id.	Type of dangerous phenomenon	Intensity of loss of containment	Time scale	Relevance based on time-scale
1	Fireball	H – Catastrophic failure	sec	Type a) – No mitigation or protection actions effective
2	Confined explosion	H – Catastrophic failure	sec	Type a) – No mitigation or protection actions effective
3a	Pool fire	H – Catastrophic failure or failure of large diameter pipe	min ÷ h	Type b) – No effective mitigation action likely, protection actions may be effective
3b	Pool fire	L – Release from low equivalent diameter rupture	min ÷ h	Type c) – Shut down, blow down and protection actions may be effective
4a	Jet fire	H – Failure of large diameter pipe	min ÷ h	Type b) – Effective mitigation action (shut down and blow-down) may be effective
4b	Jet fire	L – Release from low equivalent diameter rupture	min ÷ h	Type c) – Shut down, blow down and protection actions may be effective
5a	Toxic dispersions	H – Catastrophic failure or failure of large diameter pipe	min ÷ h	Type a) – No effective mitigation action likely, scarce effectiveness of actions likely
5b	Toxic dispersion	L – Release from low equivalent diameter rupture	min ÷ h	Type b) – Shut down, blow down and protection actions may be effective
6a	Flash-fire	H – Catastrophic failure or failure of large diameter pipe	min	Type a) – No effective mitigation or protection action likely
6b	Flash-fire	L – Release from low equivalent diameter rupture	min	Type b) – Shut down, blow down and water curtains may be effective
7a	Vapour cloud explosion	H – Catastrophic failure or failure of large diameter pipe	min	Type a) – No effective mitigation or protection action likely
7b	Vapour cloud explosion	L – Release from low equivalent diameter rupture	min	Type b) – Shut down, blow down and protection actions may be effective

H: high, L: low; sec: seconds; min: minutes; h: hours.

Table 6
Substance/installation matrix evidencing the physical state of the substance and the significant pairs.

Substance	Storage under pressure	Cryogenic storage	Storage at ambient conditions	Pipework network	Loading/unloading
LPG	Lp	Lc	E.f.n.	Lp/Lc	Lp/Lc
Chlorine	Lp	Lc	E.i.p.	G/Lp/Lc	Lp
Ammonia	Lp	Lc	Ws	G/Lp/Lc/Ws	Lp/Lc/Ws
Sulphur dioxide	Lp	E.i.p.	E.i.p.	G/Lp	Lp
Hydrogen	G	Lc	G	G/Lc	G/Lc
Hydrogen sulphide	E.i.p.	E.i.p.	E.i.p.	G	E.i.p.
Hydrogen fluoride	Lp	E.i.p.	Ws	G/Lp/Ws	Lp/Ws
LNG	E.f.n.	Lc	E.f.n.	Lc	Lc
Methanol	E.i.p.	E.f.n.	L	G/L	L
Flammable gases	G	E.f.n.	G	G	G
Flammable liquids	E.i.p.	E.f.n.	L	L	L
Ammonium nitrate	E.f.n.	E.f.n.	S	E.f.n.	E.f.n.

Key: L, liquid, non-boiling at room conditions; Lc, cryogenic liquid; Lp, liquefied in pressure; Ws, liquid solution with water; G, gas, pressurized gas; S, solid; E.f.n., excluded because of the physical nature; E.i.p., excluded because not significant in the current industrial practice (Kirk & Othmer, 2007; Ullmann, 2008).

Fig. 4 shows the validated accident scenarios obtained for the “flammable liquid” storage tank in Fig. 2. It can be observed that some of the dangerous phenomena can be excluded if specific conditions are satisfied. This allows for the quick customization of the developed generic trees (consideration of a specific ‘flammable liquid’ should account for the actual volatility, formation of toxic gases during combustion, environmental damage, etc.).

During the definition of the analysed reference schemes, several potential safety barriers are proposed. For example, the barriers typically applicable to an atmospheric storage tank include inertization, pressure/vacuum relief, high level alarm, catch basin, sprinkler system, fireproofing, segregation, hazard zoning, etc. Some of these barriers are shown in Fig. 2. The applicable barriers for the analysed reference installation were inserted into the relevant position of the bow-tie diagrams. It should be noted however that only inherent safety barriers are really capable of preventing an accident chain; the possible failure of any other type of barrier should be taken into account (Kletz & Amyotte, 2010). Therefore the effectiveness of non-inherent barriers in preventing accident scenarios should be judged case by case, and is beyond the scope of the current case study.

The detailed criteria for selecting and prioritizing accident scenarios relevant in LUP are applicable only when specific information is available about the lay-out and the thresholds assumed for

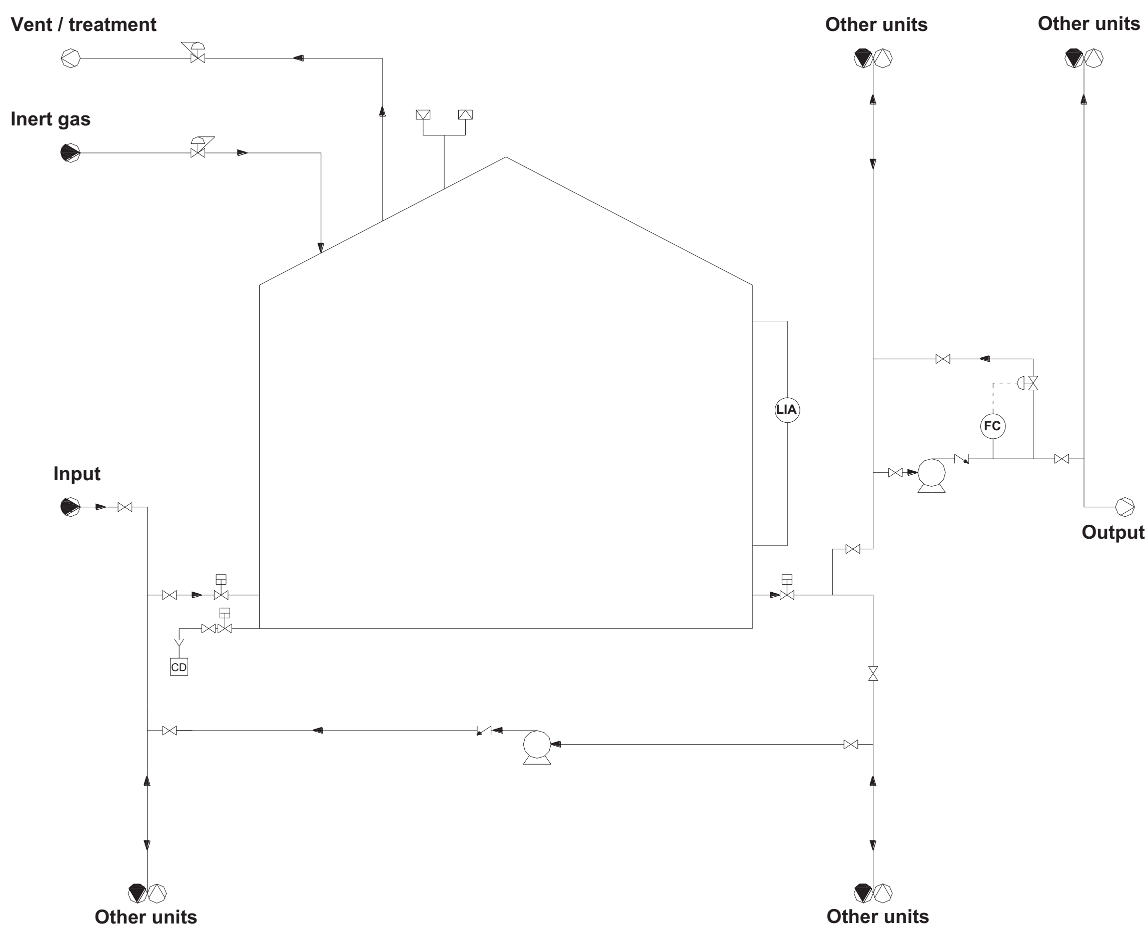

Fig. 2. Example of a reference process flow diagram (PFD) used in the assessment of an atmospheric cone-roof storage tank for flammable liquids.

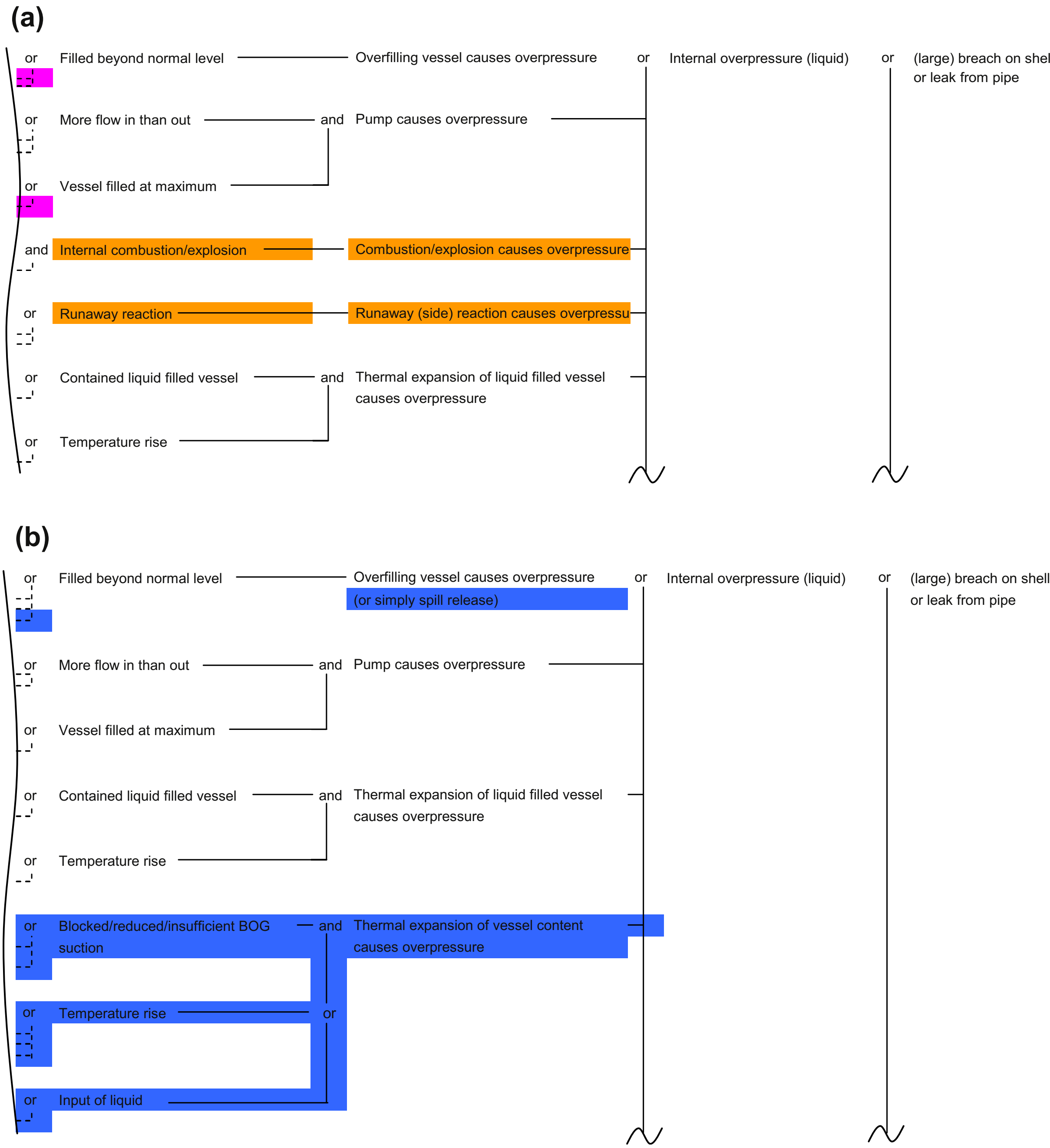

Fig. 3. Example of fault tree adaptation for an LNG storage tank: a) section of the generic fault tree from MIMAH; shaded areas refer to causes identified for possible exclusion on a preliminary basis; b) section of the validated fault tree; shaded areas refer to causes modified during the review and validation process.

off-site consequences. Therefore at this stage all of the identified possible accident scenarios are considered to be relevant for LUP and are included in the validated list. For example, Fig. 4 shows that all of the accident scenarios involve **type a** dangerous phenomena, according to at least one criterion of Table 4. Evidently, some scenarios can be excluded when a specific equipment or substance is considered instead of the generic ones. For example, the HazOp analysis of generic units evidenced that "vacuum collapse" (CE11) should be considered as a possible critical event for almost any vessel explicitly not designed to resist vacuum. Hence this scenario can be excluded only when vacuum design criteria, derived from national or international standards, are applied to the vessel. However, such information is unavailable for the generic reference schemes considered in the current case-study.

3.2. *Case-study 2 — LNG terminal*

The terminal considered in the present study receives LNG from carrier ships docked at the plant berth. Articulated arms are used for unloading and the necessary pressure is provided by pumps on-board of the carrier. A vapour compensation line is present along the berth in order to allow vapour return to carrier tanks. The LNG is stored as a cryogenic liquid in two full containment storage tanks. The regasification line consists of the tank's submerged pumps, a re-condenser, booster pumps and vaporizers. Boil-off gases from the storage tanks are compressed and sent to the re-condenser, where they contact sub-cooled LNG. The vaporizer in the plant uses the well known submerged combustion technology (SCV). Table 7 lists the units assessed in the plant, the substances handled,

Critical event	Secondary critical event	Tertiary critical event	Dangerous Phenomenon	Freq. Type	Sev. Type	T.S. Type	Note on DP inclusion
Breach on the shell in liquid phase (CE7)	Pool formation	Pool ignited	Pool fire	a	b	b^H/c^L	
			Toxic cloud	a	a	a^H/b^L	If combustion yields hazardous compounds
			Environmental damage	a	a	a^H/b^L	If combustion yields hazardous compounds
		Gas dispersion	VCE	a	a	a^H/b^L	If volatility is high at release conditions
			Flash-fire	a	a	a^H/b^L	If volatility is high at release conditions
Leak from liquid pipe (CE8)	Pool formation	Pool ignited	Pool fire	a	b	b^H/c^L	
			Toxic cloud	a	a	a^H/b^L	If combustion yields hazardous compounds
			Environmental damage	a	a	a^H/b^L	If combustion yields hazardous compounds
		Gas dispersion	VCE	a	a	a^H/b^L	If volatility is high at release conditions
			Flash-fire	a	a	a^H/b^L	If volatility is high at release conditions
Catastrophic rupture (CE10)	Catastrophic rupture	Catastrophic rupture	Missiles ejection	a	b	a	If significant internal pressure can be generated
			Overpressure generation	a	b	a	If significant internal pressure can be generated
	Pool formation	Pool ignited	Pool fire	a	b	b	
			Toxic cloud	a	a	a	If combustion yields hazardous compounds
			Environmental damage	a	a	a	If combustion yields hazardous compounds
		Gas dispersion	VCE	a	a	a	If volatility is high at release conditions
			Flash-fire	a	a	a	If volatility is high at release conditions
Vessel collapse (CE11)	Pool formation	Pool ignited	Pool fire	a	b	b	
			Toxic cloud	a	a	a	If combustion yields hazardous compounds
			Environmental damage	a	a	a	If combustion yields hazardous compounds
		Gas dispersion	VCE	a	a	a	If volatility is high at release conditions
			Flash-fire	a	a	a	If volatility is high at release conditions
Collapse of the roof (CE12)	Pool inside the tank	Pool ignited inside the tank	Tankfire	a	b	b	
			Toxic cloud	a	a	a	If combustion yields hazardous compounds
			Environmental damage	a	a	a	If combustion yields hazardous compounds
			Boilover and resulting poolfire	a	b	b	
		Gas dispersion	VCE	a	a	a	If volatility is high at release conditions
			Flash-fire	a	a	a	If volatility is high at release conditions

Fig. 4. Case study 1: accident scenarios identified for atmospheric storage of non-toxic flammable liquids (reference PFD in Fig. 2). The dangerous phenomena listed in grey boxes are included only if the conditions in the last column (notes on DP inclusion) are verified. H: release from large equivalent diameter rupture, L: release from small equivalent diameter rupture.

the operative conditions, and the quantity potentially released by the envisaged LOCs. Fig. 7 shows the fictitious plant location (Fig. 7-a) and layout (Fig. 7-b). The facility is situated on the coastline of a small gulf; the closest populated areas are located about 4 km south and 6 km north–west, and a local road transits about 2 km west from the plant.

A set of validated potential accident scenarios for the LNG terminal is obtained through the identification procedure described above. Methodology application and results obtained in these steps are similar to the previous case-study and discussion is not repeated here. Figs. 5 and 6 show examples of the potential accident scenarios identified for two selected units (re-condenser column and diesel storage tank). The customization of units and materials affects the scenarios identified (e.g. LNG and its vapours are not toxic, but only asphyxiant at high concentrations). Another example is provided by the comparison of Figs. 4 and 6, the first referring to a generic atmospheric storage of flammable liquids, the second to the specific case of the diesel fuel tank of the considered plant. Diesel has low volatility, the combustion does not produce highly toxic substances, and no environmental damage is expected (adequate management of firefighting waters is considered here); therefore the dangerous phenomena are limited to pool fires and explosion in the case of a catastrophic collapse.

Figs. 5 and 6 report the results obtained by applying the screening matrix of Table 4 to the accident scenarios. In the figures the contribution of each single dangerous phenomenon to the classification of LUP relevance is shown. The three main criteria identified in the consultation matrix (frequency, severity and time scale) were quantified and classified according to the three classes proposed for LUP accident scenarios (**type a, b, and c**). Reported frequencies were estimated from the reference values for LOC frequencies and ignition probabilities proposed in the Purple Book (Uijt de Haag & Ale, 2005). In the case of the re-condenser column (Fig. 5), the consultation matrix suggests considering for LUP purposes all of the accident scenarios, though a few dangerous phenomena, evaluated individually, may be omitted. On the other hand, the analysis of the diesel storage tank (Fig. 6) leads to vacuum collapses and roof collapses being identified as **Type b** scenarios.

The safety barrier criterion is not explicitly evidenced in Figs. 5 and 6. As a matter of fact, no passive barrier can completely prevent accident scenarios for the units analysed, as an examination of the associated bow-ties can show. On the contrary, the introduction of inherent safety barriers may prevent a few accident scenarios from happening (Tugnoli et al., 2012). For instance this is the case of the vessel collapse (CE11) for the re-condenser column, where vessel design inherently protects from vacuum implosion. In such cases, however, the barrier is directly recognized during the tree customization procedure without requiring further assessments.

Table 8 reports the accident scenario type class for all of the plant units. This is obtained by considering the class with the most severe rank among all the categories and all the dangerous phenomena for any given accident scenario. A large number of **Type a** accident scenarios (i.e. "must be considered for LUP") are identified. This is an expected result given the number of units in the plant that handle a highly flammable liquefied gas. **Type b** accident scenarios are identified for the sections where less dangerous materials are handled (e.g. diesel fuel). These scenarios can be disregarded *a priori* only if the applicable LUP legislation defines specific indications (e.g. cut-off criteria for accident scenario frequencies).

Finally, Fig. 7 provides an example of the damage areas calculated for the accident scenarios identified above. Clearly enough, the actual definition of damage areas depends on the LUP regulation applicable in the plant location. In the figure, the contours identify the "worst case" zone where damage effects exceed a given set of thresholds. Threshold values were arbitrarily chosen as follows: overpressure 14 kPa, stationary heat radiation 7 kW/m^2, flash-fire envelope concentration LEL/2. These values were selected considering the limit for possible lethal effects as defined by the Italian LUP legislation (Ministero dei Lavori Pubblici, 2001). The distances from the release point at which the effect of a dangerous phenomenon reaches the relevant threshold were calculated using models described in the TNO's "Yellow book" (Van Den Bosh & Weterings, 1997). A single weather condition (Pasquill stability class F; wind speed 2 m/s) was considered. This "worst case" contour was defined considering the maximum distance among possible scenarios (Tugnoli et al., 2012). In total five representative "worst case" contours are reported in the figure: (i) flash fire from full bore rupture of LNG transfer arm (stream 1a); (ii) flash fire from the catastrophic rupture of the LNG storage tank (D01); (iii) flash fire from the catastrophic rupture of the vaporizer (E12); (iv) pool fire from large breach of the diesel tank (D03); (v) pool fire from full bore rupture of diesel pipework (stream 17). The figure shows that some accident scenarios may not extend beyond plant limits and, thus, can be neglected for LUP purposes (e.g. diesel storage tank and pipework). On the contrary, actual LUP measures are needed for the areas located far beyond the plant boundaries when affected by some of the identified scenarios (e.g. scenarios form LNG storage tanks and unloading arms). These measures should be defined on the basis of the local LUP legislation (Basta, Neuvel, Zlatanova, & Ale, 2007; Christou et al., 1999, 2006; Cozzani et al., 2006).

4. Results and discussion

Fig. 4 reports an example of the general LUP scenarios identified in case-study 1 for the reference installations. In particular, the

Table 7
Main features of the units assessed in case study 2. L: Liquid; G: Gas; NG: Natural gas.

ID	Name	Type	Substance	State	Boiling temp. (°C)	Service temp. (°C)	Vol (m^3)	Mass (kg)
D01–02	Storage tank	EQ7	LNG	L	−161	−161	44,000	20,030,000
P01	Blower/compressor	EQ16	NG	G	−161	−130	/	1500
P02–03	Compressor	EQ16	NG	G	−161	−8	/	1330
P04	Compressor	EQ16	NG	G	−161	−8	/	330
C01	Recondenser	EQ12	LNG	L	−161	−161	/	56,000
G15–18	Pump	EQ16	LNG	L	−161	−161	/	18,600
E11–14	Vaporizer	EQ14	LNG	L	−161	5	/	18,600
1a	LNG arm	EQ10	LNG	L	−161	−161	/	152,000
4	Balance gas arm	EQ10	NG	G	−161	−130	/	1500
2	Berth LNG line	EQ10	LNG	L	−161	−161	/	304,000
3	Berth gas line	EQ10	NG	G	−161	−130	/	1500
16	Send-out line	EQ10	NG	G	−161	5	/	56,000
D03	Diesel tank	EQ6	Diesel fuel	L	240	25	51	34,600
17	Diesel pipework	EQ10	Diesel fuel	L	240	25	/	2300

Critical event	Secondary critical event	Tertiary critical event	Dangerous Phenomenon	Freq. (1/y)	Freq. Type	Sev.	Sev. Type	T.S.	T.S. Type
Breach on the shell in vapour phase (CE6)	Gas jet	Gas dispersion	VCE	2×10^{-5}	a	VCE	a	7b	b
			Flash-fire	3×10^{-5}	a	FF	a	6b	b
			High concentration of gas	5×10^{-5}	a	HC	b	5b	b
		Gas jet ignited	Jet-fire	1×10^{-6}	a	JF	b	4b	c
Breach on the shell in liquid phase (CE7)	Pool formation	Pool ignited	Pool fire	1×10^{-6}	a	PF	b	3b	c
		Gas dispersion	VCE	2×10^{-5}	a	VCE	a	7b	b
			Flash-fire	3×10^{-5}	a	FF	a	6b	b
			High concentration of gas	5×10^{-5}	a	HC	b	5b	b
	Release of cryogenic liquid / two-phase jet	Release of cryogenic liquid	Release of cryogenic liquid	5×10^{-5}	a	CL	b	5b	b
Leak from liquid pipe (CE8)	Pool formation	Pool ignited	Pool fire	1×10^{-6}	a	PF	b	3b	c
		Gas dispersion	VCE	2×10^{-5}	a	VCE	a	7b	b
			Flash-fire	3×10^{-5}	a	FF	a	6b	b
			High concentration of gas	5×10^{-5}	a	HC	b	5b	b
	Release of cryogenic liquid / two-phase jet	Release of cryogenic liquid	Release of cryogenic liquid	5×10^{-5}	a	CL	b	5b	b
Leak from gas pipe (CE9)	Gas jet	Gas dispersion	VCE	2×10^{-5}	a	VCE	a	7b	b
			Flash-fire	3×10^{-5}	a	FF	a	6b	b
			High concentration of gas	5×10^{-5}	a	HC	b	5b	b
		Gas jet ignited	Jet-fire	1×10^{-6}	a	JF	b	4b	c
Catastrophic rupture (CE10)	Catastrophic rupture	Catastrophic rupture	Missiles ejection	1×10^{-5}	a	CE	b	2	a
			Overpressure generation	1×10^{-5}	a	CE	b	2	a
	Pool formation	Pool ignited	Pool fire	9×10^{-7}	b	PF	b	3a	b
		Gas dispersion	VCE	4×10^{-6}	a	VCE	a	7a	a
			Flash-fire	5×10^{-6}	a	FF	a	6a	a
			High concentration of gas	9×10^{-6}	a	HC	b	5b	b
	SCE8 Aerosol puff	Gas dispersion	VCE	4×10^{-6}	a	VCE	a	7a	a
			Flash-fire	5×10^{-6}	a	FF	a	6a	a
			High concentration of gas	9×10^{-6}	a	HC	b	5b	b
		Aerosol puff ignited	Fireball	9×10^{-7}	b	FB	a	1	a
	Release of cryogenic liquid	Release of cryogenic liquid	Release of cryogenic liquid	1×10^{-5}	a	CL	b	5b	b

Fig. 5. Accident scenarios identified for the re-condenser column (C01) of case-study 2 and application of the screening matrix.

Critical event	Secondary critical event	Tertiary critical event	Dangerous Phenomenon	Freq. (1/y)	Freq. Type	Sev.	Sev. Type	T.S.	T.S. Type
Breach on the shell in liquid phase (CE7)	Pool formation	Pool ignited	Pool fire	$7x10^{-6}$	**a**	PF	**b**	3b	**c**
Leak from liquid pipe (CE8)	Pool formation	Pool ignited	Pool fire	$4x10^{-6}$	**a**	PF	**b**	3b	**c**
Catastrophic rupture (CE10)	Catastrophic rupture	Catastrophic rupture	Missiles ejection	$3x10^{-7}$	**b**	CE	**b**	2	**a**
			Overpressure generation	$3x10^{-7}$	**b**	CE	**b**	2	**a**
	Pool formation	Pool ignited	Pool fire	$3x10^{-7}$	**b**	PF	**b**	3a	**b**
Vessel collapse (CE11)	Pool formation	Pool ignited	Pool fire	$3x10^{-7}$	**b**	PF	**b**	3a	**b**
Collapse of the roof (CE12)	Pool inside the tank	Pool ignited inside the tank	Tankfire	$3x10^{-7}$	**b**	PF	**b**	3a	**b**
			Boilover and resulting poolfire	$3x10^{-7}$	**b**	PF	**b**	3a	**b**

Fig. 6. Accident scenarios identified for the diesel storage tank (D03) of case-study 2 and application of the screening matrix.

figure shows the accident scenarios obtained for the storage installation in Fig. 2. Similar results, having the same level of detail, were obtained for all the other significant substance/installation pairs identified in Table 6 and were not reported for the sake of brevity.

The results of case-study 1 take advantage from the fact that typical installation schemes can be defined for the storage and pipework of the more common hazardous materials used in industrial practice. Hence, case-study 1 suggests that the preliminary identification and characterization of a set of “LUP-relevant” accident scenarios can be achieved starting from generic reference schemes and thereby providing a benchmark for a more consistent assessment practice of these facilities in the EU. In the light of these results, the development of a generic guide appears to be valid and useful, containing the relevant scenarios for LUP to support EU Member States in implementing Article 12 of the Seveso Directive. The results of case-study 1 may be interpreted as a possible input into the knowledge system.

Altogether, the results of the application in case-study 1 emphasize that the credibility of causes and the effectiveness of safety barriers is not easy to assess on a generic basis, since it strongly depends on the design of any single installation. Therefore no “blind-use” is advised for generic scenarios, but validity of causes and existence and effectiveness of safety barriers must be assessed case by case. When site-specific information is available for the considered installation, it is possible to further assess the generic accident scenarios by the criteria in Table 4 and to account for the actual installed safety barriers. An example of this procedure was demonstrated in case-study 2.

Nevertheless, the reference checklist of possible relevant scenarios and the extensive set of customized bow-tie diagrams for the significant substance/installation couples listed in Table 6 provided by the methodology in case study 1 may be used as a validated starting point for the assessment of specific installations. This is mostly practical in the case of widely used and technically “simple” facilities or plant sections (e.g. hazardous material storage, loading/unloading, transfer), for which generic considerations can be easily tailored.

Case-study 2 illustrates the application of the consultation matrix. Figs. 5 and 6 show the contribution of the single dangerous phenomenon to the scenario classification. Significant variations in classes may occur among the different criteria, confirming that all

Table 8
Results of accident scenario prioritization in case-study 2.

ID	Name	CE6 Breach on the shell in vapour phase	CE7 Breach on the shell in liquid phase	CE8 Leak from liquid pipe	CE9 Leak from gas pipe	CE10 Catastr. rupture	CE11 Vessel collapse	CE12 Collapse of the roof
D01–02	Storage tank	Type a)	Type a)	Type a)	Type a)	Type a)	Type a)	Type a)
P01–04	Blower/compressor	–	–	–	Type a)	Type a)	–	–
G15–18	Pump	–	–	Type a)	–	Type a)	–	–
C01	Recondenser	Type a)	Type a)	Type a)	Type a)	Type a)	–	–
E11–14	Vaporizer	–	–	Type a)	Type a)	Type a)	–	–
1a	LNG arm	–	–	Type a)	–	–	–	–
4	Balance gas arm	–	–	–	Type a)	–	–	–
2	Berth LNG line	–	–	Type a)	–	–	–	–
3	Berth gas line	–	–	–	Type a)	–	–	–
16	Send-out line	–	–	–	Type a)	–	–	–
D03	Diesel tank	–	Type a)	Type a)	–	Type a)	Type b)	Type b)
17	Diesel pipework	–	–	Type a)	–	–	–	–

Fig. 7. Case-study 2: fictitious plant location (panel a) and layout (panel b). Dashed lines mark worst case damage contours discussed in the text for selected units: (i) LNG unloading arm (stream 1a); (ii) LNG storage tank (D01); (iii) vaporizer (E12); (iv) diesel tank (D03); (v) diesel pipework (stream 17).

of the four criteria are necessary to obtain a comprehensive picture of the LUP relevance of the scenario. The adoption of conservative criteria in the selection of accident scenarios leads to the comprehensive results summarized in Table 8.

In the analysis of the final results in Table 8, it is important to remark that **Type b** scenarios should not be automatically disregarded. The classification provided by the methods should rather be interpreted as a guide to consider thoughtfully all **Type a** scenarios rather than the possibility to discard **Type b** scenarios. The classification reflects an order of priority in the analysis of scenarios.

Nevertheless, Country-specific LUP criteria will play the major role in the final assessment of the LUP relevant scenarios. For example, a catastrophic failure of a LNG storage tank in case-study 2 (a type a) scenario would potentially affect the area marked by contour (ii) in Fig. 7 (the flash fire may potentially affect targets up to 3400 m from the release point). The classification provided by the consultation matrix suggests that this scenario must be considered in the assessment of the plant, due to the potentially very severe consequences as clearly shown by the extension of the damage area. This confirms that the identification of such a scenario, despite its extremely low frequency, is a valuable result of the identification phase. The measures that are actually implemented in the damage area are dependent however on the applicable LUP legislation (e.g. no sensitive targets allowed, only low density residential areas, etc.) and on its structure (risk based approaches may discard the scenario due to sufficiently low expected frequency; consequence-based regimes may ignore some safety barriers which only reduce accident frequency). This is, in fact, a matter of safety policy in each country and may involve tradeoffs among different priorities. Nevertheless, the availability of a validated list of LUP relevant scenarios is at the foundation of any LUP decision of this kind.

5. Conclusions

A procedure to support the identification and ranking in order of relevance of accident scenarios for land-use planning purposes is developed. Although the procedure is based on the framework provided by the EU Directive 96/82/EC, it retains a generic structure that allows its application in other Countries that implement different LUP legislations. The procedure incorporates a modified MIMAH methodology, specifically developed for the identification and the validation of accident scenarios. To help achieving consistency in LUP decision making, the relevance of the accident scenarios is assessed against four criteria: (a) frequency, (b) severity, (c) presence and effectiveness of safety barriers, and (d) time scale of the scenario. Overall, the methodology yields a complete set of validated generic bow-ties that can be used in the following phases of LUP procedures (definition of site-specific scenarios and decision-making). The methodology was applied to two case-studies of industrial interest. In both cases, the proposed methodology successfully generated consistent sets of reference accident scenarios. The results obtained are well in line with initiatives at the European level for promoting a consistent application of LUP criteria.

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Nomenclature

CE	confined explosion
CL	cryogenic liquid spreading
DP	dangerous phenomena in MIMAH approach
EC	critical events in MIMAH approach
EQ	equipment class in MIMAH approach
EU	European Union
FB	fireball
FF	flash-fire
G	gas phase

H/L	high/low
HazOp	hazard and operability assessment
HC	high concentration of gas (asphyxiation)
JF	jet-fire
L	liquid phase
LNG	liquefied natural gas
LOC	loss of containment event
LPG	liquefied petroleum gas
LUP	land use planning
MIMAH	Methodology for the Identification of Major Accident Hazards
MS	member states of the European Union
NG	natural gas
PF	pool fire
SCV	submerged combustion vaporizer
T.S.	time scale
VCE	vapour cloud explosion

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