A MULTI-CRITERIA AND FUZZY LOGIC BASED METHODOLOGY FOR THE RELATIVE RANKING OF THE FIRE HAZARD OF CHEMICAL SUBSTANCES AND INSTALLATIONS

A.N. Paralikas and A.I. Lygeros
School of Chemical Engineering, National Technical University of Athens, 15780 Zografos Campus, Athens, Greece; e-mail: aparal@tee.gr

No single property can be used for assessing the fire hazards of chemical substances and materials; different methods use different fire hazard properties in their assessment. On the other hand, current methodologies and classification systems usually use linguistic variables corresponding to specific range of values, for the classification of different hazards. Moreover, many uncertainties are present in the assessment of industrial hazards or industrial accidents consequences.

In this paper, a new approach for the rapid assessment and relative ranking of the hazards of chemical substances, as well as units and installations, is presented. This approach is based on employing a multi-criteria decision-making technique (the Analytic Hierarchy Process) for the hazard assessment of substances and installations. The multi-criteria approach aims in the better incorporation of the different properties or parameters in hazard assessment. This approach is also based on fuzzy logic. Fuzzy logic is considered better for dealing both with linguistic variables and uncertainties.

A number of Indices have been developed, based on the proposed methodology and are presented: the *'Substance Fire Hazard Index', (SFHI)*, which is focused on the major-accident hazards of the substances, and the *'Consequences Index', (CI)*, for the assessment of the consequences potential of an accident at the facility. The challenges and limitations of using the multi-criteria approach for the development of such indices are also discussed.

KEYWORDS: Analytic Hierarchy Process; Fuzzy sets; Hazard Indices.

INTRODUCTION

The management of risks resulting from industrial activities constitutes one of the bigger challenges chemical industry faces nowadays. A first step for the management of risks is hazard identification and assessment, which requires systematic and methodical study and analysis of the hazards. For this purpose, a wide range of hazard identification and assessment techniques has been developed. Among them are relative assessment and ranking techniques[1,2,3]. These techniques are aiming at the assessment of hazards and threats, without the commitment of many resources, in manpower and time. The most known and widespread techniques of this kind are Dow 'Fire & Explosion Index'[4] and ICI 'Mond' index[5], which are widely used for the rapid hazard assessment of installations that use hazardous substances. A number of similar indices have been proposed for the case of toxic[6,7], ecotoxic[8] and reactive substances[9]. Recent developments in this field include, among other, indices developed by F.I. Khan and colleagues[10,11,12], or indices focused on Inherent Safety[13,14,15]. Tixtier et al[16] have recently presented a collection and comparative analysis of 62 hazard and risk analysis methodologies, including many indices, relative assessment and ranking techniques.

'No single fire hazard property, such as flash point or ignition temperature, should be used to describe or appraise the fire hazard or fire risk of a material, product, assembly, or system under actual fire conditions'[17]. Moreover 'there is no single parameter which defines flammability, but some which are relevant are: a) flash point, b) flammability limits, c) auto-ignition temperature, d) ignition energy and e) burning velocity'[18]. 'The fire hazard properties may be used as elements of a fire risk assessment only when such assessment takes into account all of the factors that are pertinent to the evaluation of the fire hazard of a given situation.'[17] Different methods, tools, codes, legislation requirements, guidelines,[19,20], etc, use varying sets of fire hazard properties to access the fire hazards of chemical substances. Such properties included, for example, are the above mentioned parameters, outlined by F.P. Lees[18], or those described in NFPA 325 *Guide to Fire Hazards Properties of Flammable Liquids, Gasses & Volatile Solids*[17], namely: flash point, ignition temperature, flammable (explosive) limits, specific gravity (relative density), vapour density, boiling point, melting point, water solubility.

The scope of this paper is to introduce a new methodology for developing safety-related indices, aimed at the relative ranking and comparative assessment of hazardous substances, hazardous installations, units, or processes. The proposed methodology views the issue of relative assessment and ranking as a multi-criteria decision-making problem; therefore aims in incorporating the different decision criteria in the assessment. For the incorporation of the different criteria or parameters in the calculation of the developed indices, a multi-criteria analysis technique, Analytic Hierarchy Process (AHP)[21], has been employed. Furthermore, the development of the proposed methodology was also based on fuzzy logic concepts.

Based on the proposed methodology two indices, the 'Substance Fire Hazard Index', *SFHI*, and the 'Consequences Index', *CI*, have been development and are presented, in order to demonstrate the application of the methodology. *SFHI* is proposed as a tool for the relative ranking and comparative assessment of hazardous substances, according to their fire hazard properties. The proposed index is focused on estimating the fire hazards of the substances related to accidents that could take place at installations that use, process, produce, or store hazardous substances. The calculation of the proposed index is based on a total of 15 hazardous properties. The 'Consequences Index', *CI*, is introduced as a tool for the ranking of industrial facilities and units that use hazardous substances, according to the magnitude of the possible consequences, posed on the installation as well as the natural and human environment around it, from a possible accident at the installation. The proposed methodology could also be used for the development of similar indices, based on any organization's need and views. Also the proposed indices could be modified by any user to include their own priorities, or decision environment.

This paper is organized as follows: in section 2 principles of fuzzy sets theory are presented; in section 3 Analytic Hierarchy Process is described; in section 4 the proposed methodology is outlined. In Sections 5 and 6 the developed indices based on the proposed methodology are presented. Finally, in Section 7, some conclusions are presented.

FUZZY SETS CONCEPTS

Fuzzy Sets theory was introduced by L. Zadeh in 1965[22] to deal with imprecision, uncertainty and vagueness that are inherent in many 'real world' problems[23]. Since then, there have been many successful applications of fuzzy sets and fuzzy logic, including chemical process safety and assessment related issues, as described, for example, in refs.[24–31]. In this section, some basic concepts of fuzzy sets are presented. More details on fuzzy sets and fuzzy logic can be found in refs.[23,32–35].

Central point in fuzzy sets theory is the notion of membership. In classic sets, an element may or may not belong to a given set. In fuzzy sets, an element may belong to a set up to some degree, called degree of membership, which takes values between 0 and 1. Among the fuzzy sets that are of more importance, those that their membership functions can be represented by parameterizable mathematical functions are included. Known as 'fuzzy numbers', such fuzzy sets allow the performance of arithmetic operations. Most common shapes of fuzzy numbers, which are also used in this work, are triangular and trapezoid fuzzy numbers.

Fuzzy numbers can be used effectively to describe Linguistic Variables, such as 'very tall', 'tall'[21]; furthermore, they can be used for handling qualitative data (e.g. 'slightly soluble', etc.). In existing hazard classification systems, the levels, classes or categories of the various hazardous properties of chemical substances are usually determined with the use of intervals that are defined by 'crisp' boundaries. For example, according to NFPA 704[36], a substance (e.g. *gasoline*) with flash point −43°C has Fire Hazard Rating '4'. The same rating applies to a substance with flash point 13°C (e.g. *Ethanol*), while, a substance with flash point 32°C (e.g. *Xylene*), has Fire Hazard Rating '3' and *Kerosene*, with flash point 37,8°C, has Fire Hazard Rating '2'.

As it will be described later on, fuzzy linguistic variables have been used in the development of the proposed index, for describing the various levels, classes or categories of each hazardous property, and also in the development of utility functions for assigning penalty values to each hazardous property.

AHP: AN OUTLINE

Multi-criteria decision models are receiving increasing attention in dealing with complex problems issues. The use of decision-making tools, among them Analytic Hierarchy Process (AHP), has been suggested for the assessment of chemical accident hazards[37–38]. AHP, developed by T.L. Saaty in late 70s[21], is designed to deal with complex decision-making problems involving multiple criteria, in a wide range of application fields[39]. It can be used for ranking decision alternatives, based on a set of parameters that are taken into account in the assessment. The assessment and ranking of fire hazards of chemical substances, facilities that use produce or store hazardous substances, process units, etc, can be viewed as such a complex problem, with multiple parameters involved; various substances, facilities, process or units can be viewed as decision alternatives. AHP allows for intangible and quantitative factors to be successfully involved in the assessment process. It has been employed in fire safety assessment of buildings and structures[40–42], in process selection, as well as safety issues[43–45]. As it has been mentioned already, no single fire hazard property can be used to describe or appraise the fire hazards or risks of materials; therefore AHP is suitable for incorporating different parameters in the assessment.

Two major steps can be distinguished in the procedure: First, structuring the problem under consideration in a hierarchical form. This involves 'decomposition' of the problem into components, namely the identification of the parameters that are considered as relevant, as well as the organization of these parameters in groups and sub-groups, which are then linked in a hierarchical manner. This results in forming the Hierarchy, the hierarchical structure that is representative of the analysis of the specific problem. The lowest level of the Hierarchy is constituted by the alternatives, or, in the 'ratings' mode, by the parameters that are employed in the assessment. This mode is suitable in cases of large number of alternatives or in the case of development of a general index. In this case, the assessment is performed in a spreadsheet manner, where for each parameter a Weight Factor is assigned and for the different alternatives, relevant Penalty Factors that represent the magnitude of each parameter are assigned.

Second step is the assignment of weights to each parameter or factor of the problem. This is done though pair-wise comparative judgments among all parameters that belong to the same group or sub-group. The parameters are compared in respect to their importance, likelihood or preference, depending on the nature of the problem under consideration. The pair-wise comparisons are performed by an expert, or group of experts, capturing their knowledge, expertise or understanding, which are incorporated in the final results. To compare parameter ith with parameter jth, the decision-maker assigns a linguistic value a_{ij}, which corresponds to a numeric value, an integer in the range 1–9. The meaning of each value on the scale is presented in Table 1.

Pair-wise comparisons of all elements within each group or subgroup form an $n \times n$ matrix, A. Rows and columns of the pair-wise comparisons matrix are the n elements of the respective group or sub-group. The local priorities vector on the group's or subgroup's elements is elicited from the eigen-vector that corresponds to the maximum eigenvalue of matrix A. The synthesis of the local priorities of all levels results to the weight vector of the priorities of all parameters taken into account.

One important advantage of AHP is the consistency check, which provides an indication of the consistency among the pair-wise judgments. One of its disadvantages,

Table 1. The pair-wise comparisons scheme used in AHP

$a_{ij} = 1$	The two parameters are **equally** *important* (*likely/preferred, etc ...*)
3	parameter i is **weakly** *more important* than parameter j.
5	parameter i is **strongly** *more important* than parameter j.
7	parameter i is **very strongly** *more important* than parameter j.
9	parameter i is **absolutely** *more important* than parameter j.
2,4,6,8	interval values between to adjacent choices.

on the other hand, is its inability to deal with problems that cannot be represented by a strict hierarchical structure, namely when there are interconnections or interdependencies among parameters or elements of different subgroups of the same or different levels. For dealing with this problem, an extension of AHP, the Analytic Network Process, ANP, has been introduced[46]. ANP allows for feedback among different elements to be taken into account in the ranking of the alternatives. Nevertheless, the number of alternatives cannot exceed a threshold (7–9), because of the size of the 'Supermatrix' that is formed.

A final step, assigning Penalty Factors representative of the value of the respective parameter under consideration, is also included when the assessment is performed using the 'ranking' mode and not the pair-wise comparisons among the alternatives. The procedure developed in the proposed methodology for assigning Penalty Factors is described later in this paper.

THE PROPOSED METHODOLOGY

The development of the proposed methodology for the relative assessment and ranking of hazardous substances and facilities that use, produce or store hazardous substances was based on the above-mentioned approach. Each index based on the proposed methodology is constructed, first by determining the criteria – parameters taken into account in the calculation and then, by organizing them in a hierarchical manner. This leads to the development of the Hierarchy and, through pairwise comparisons among all elements belonging to the same group or subgroup at all levels of the hierarchical structure, to the assignment of relative weights, W_j, to each parameter. Finally, a penalty factor, P_j, is assigned to each parameter. The combination of the Weight Factors and the respective Penalties for each parameter provides the total value of the relative ranking for the element under consideration:

$$I_S = \sum_j W_j P_j^S \tag{1}$$

where, W_j is the Weight factor of the j Parameter, and P_j^S is the Performance measure, or Penalty factor, attributed to the jth Parameter.

The respective steps for the development of the proposed indices are outlined as following:

a) Determination of the criteria — parameters taken into account in the index calculation.
b) Procedure for the determination of the Weight factor, W_j, of the jth criterion — parameter, and
c) Development of utility functions (or value functions) for the calculation of the Performance measure (or Penalty), P_j^S, attributed to the j criterion — parameter for the Sth substance/facility.

Following in the next sections the above-mentioned steps are presented in more detail.

THE PROPOSED *'SUBSTANCE FIRE HAZARD INDEX'*

The proposed *'Substance Fire Hazard Index', SFHI*, is introduced as a tool for the relative ranking and comparative assessment of hazardous substances, according to their fire hazard properties. The calculation of the proposed index is based on a total of 15 properties, which include fire hazard properties, physical properties, special hazard properties and burning properties of chemical substances. The proposed index is focused on the estimating the fire hazards that are related to accidents that could take place at installations that use, process, produce, or store hazardous substances.

The steps that have been followed for the development of the Substance Fire Hazard Index, are presented in more detail.

FIRE HAZARD PROPERTIES TAKEN INTO ACCOUNT

First stage in the development of the proposed *SFHI*, was the determination of the fire hazard properties that would be taken into account in the development and calculation of the index. For their determination, all relevant substance properties related to this behavior of chemical substances under conditions of an accident were recorded. Those to be incorporated in calculation of the Substance Fire Hazard Index, 15 in total, were then selected. For the determination of those properties, the following sources were taken into account.

Chemical substances classification and labeling systems: *Globally Harmonized System for the Clas-sification and Labeling of Chemicals–GHS*[47]; Hazardous chemicals legislation: US. DOT Hazardous Materials Regulations[48], E.U. 'Seveso' Directive[49]; Codes, guides and guidelines: *NFPA 30*[50], *NFPA 325*[17], NFPA 49[19], CCPS, *Guidelines for Engineering Design for Process Safety*[20], US.EPA, *Hand-book of Chemical Hazard Analysis Procedures*[51]; risk evaluation models[52]; fire safety literature[53–56].

Properties identified and selected were classified in groups and subgroups, as presented in Table 2.

DETERMINATION OF WEIGHTING FACTORS, W_j

Second stage in the development of the proposed index was development of the procedure for the determination of the weights for each parameter/property taken into account in the index calculation. For each Parameter, I_j, a Weighting Factor W_j has to be ascribed. For the determination of the Weighting Factors, Analytic Hierarchy Process has been employed. First step in the implementation of AHP, as it has already been described, is the development of the Hierarchy, the hierarchical structure, which represents the problem under consideration. The Hierarchical structure developed and used is shown in Figure 1. Then the user of the proposed index will have to perform the pair-wise comparisons among all elements of each subgroup, also shown in Figure 1, at all levels of the hierarchy, in order to elicit the weights of the parameters, according to his/her own perception and understanding of the problem.

Table 2. Hazard properties taken into account in substance fire hazard index calculation

1. Fire Hazard Properties
1.a. Flash Point
1.b. Ignition Temperature
1.c. Flammability Limits
    1.c.i. Lower Flammability Limit (LFL)
    1.c.ii. Flammability Range

2. Special Hazards
2.a. Explosives
2.b. Self Reactive
2.c. Self Heating
2.d. Water reactivity
2.e. Oxidizing
2.f. Organic Peroxides

3. Physical Properties
3.a. Boiling point,
3.b. Vapor density,
3.c. Specific gravity,
3.d. Water solubility,
3.e. Vapor pressure

4. Burning Properties
4.a. Heat of Combustion ΔH_C.

The volume of the pair-wise comparisons produces the 'local' weights or priorities, which are then synthesized to produce the final Weight Factors, W_j, of the parameters. For performing these calculations and for developing the hierarchy, a software program, 'Expert Choice 2000'[57], has been used.

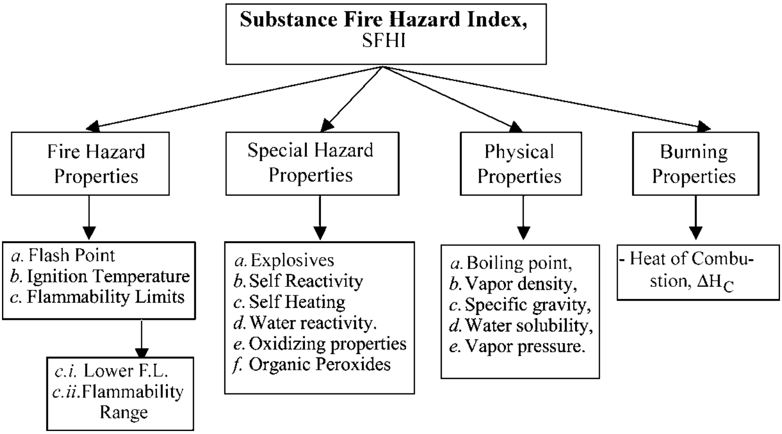

Figure 1. Hierarchical structure of the Hazard Properties taken into account in SFHI calculation

ASSIGNMENT OF PENALTIES, P_j^S

Third stage in the development of the proposed index was development of the procedure for assigning Penalty Factors, P_j^S, to the parameters (hazardous properties), I_j, taken into account in the calculation of the index. The development of this procedure was based on fuzzy logic, as well as on AHP. These Penalty Factors are representative of the value T_j^S, of the respective hazardous property I_j, for the Sth substance or material under consideration. For the assignment of Penalty Factors a 'Utility Function' (or value function) has been developed of for each one of the parameters taken into account. The steps of the procedure for the development of the Utility Functions are outlined as following:

(i) Development of Linguistic Variables for each parameter-property.
(ii) Assignment of a weight factor to each Linguistic Value that composes the Linguistic Variable.
(iii) Calculation of the Penalty Factor.

Development of Linguistic Variables for each parameter-property

The various hazardous properties taken into account in the calculation of the proposed index have been described as a set of Linguistic Variables, which represent the various levels, classes or categories of the hazardous properties of chemical substances. These classes are usually determined with the use of intervals that are defined by 'crisp' boundaries; examples are provided in the following tables. The Linguistic values that compose each Linguistic Variable were then represented as triangular or trapezoid fuzzy numbers. In order to develop the Linguistic Variables and the Linguistic values of each Variable, all major classification systems for each property were examined and their levels, classes or categories, as well the crisp boundaries of each such level, class or category, were recorded. Different classification systems may use different number of classes, or these classes may correspond to different values or value intervals; even different definitions of hazardous properties are being used. Based on these recordings, the Linguistic values of each Variable were determined, and then the fuzzy numbers that represent each value. For example, for the property 'Flammability' which depends mainly of Flash Point, the following classes for the classification of flammable liquids are determined in two major classification systems, *GHS*[47] and NFPA 30, 1996 ed.[50].

Based on the above-mentioned classification systems, codes, etc, 5 levels, or classes, for 'Flammability' where developed for use in the proposed index. These classes where then described as triangular or trapezoid fuzzy numbers, fn_k. Both are presented in Table 4 and pictured in the Figure 2.

Introducing the value T_j^S of the property I_j of the substance S in the above diagram, produces the membership degree, m_j^k, of the specific value to each one of the fuzzy linguistic terms. The degrees of membership belong to the interval [0,1] ($0 \leq m_j^k \leq 1$), and are used for the determination of the Penalty Factor that corresponds to the specific value T_j^S, as it will be described in the following paragraphs.

Table 3. 'Flammability' classes in NFPA 30 and GHS

GHS		*NFPA 30*	
Class	Limits	Class	Limits
		Flammable	
1	B.P. =<35°C.	I A	F.P. <22,8°C & BP <37,8°C
2	B.P. >35°C & F.P. > 23°C.	I B	F.P. <22,8°C & B.P. >37,°C
3	B.P. >35°C & 23° C <F.P. 37,8°C	I C	22,8°C < F.P. < 37,8°C
		Combustible	
4	60°C < F.P. < 93°C	II	37,8°C < F.P. < 60°C
		III A	60°C < F.P. < 93°C
		III B	F.P. >93°C

Assignment of a weight factor to each Linguistic Value that composes the Linguistic Variable

Next step for the development of the procedure for assigning the Penalty Factors P_j^S, is the assignment of a weight factor, w_k, to each linguistic value, k, of each Linguistic Variable. For this purpose AHP was also employed, through pairwise comparisons among all linguistic values, based on their relative importance. The weight factors, w_k, assigned to the linguistic values, k, of the Linguistic Variable 'Flash Point', are presented in Table 5.

Calculation of the Penalty Factor

The Penalty Factor, P_j^S, is calculated through the combination of the membership degrees, m_j^k, of the property value, T_j^S, for the Sth substance, to each linguistic value, and the weight factors, w_k, of each linguistic value. This combination is performed using the following relation:

$$P_j^S = \frac{\sum_k m_{jk}^S * w_k^j}{\sum_k m_{jk}^S} \tag{2}$$

Table 4. Class descriptions, boundaries and fuzzy numbers for 'flammability'

Class Description	E.F.: Extremely Flammable	V.F.: Very Flammable	F.: Flammable	S.F.: Slightly Flammable	C.: Combustible
Flash Point boundaries (°C)	<23	23–35	35–60	60–90	>90
Fuzzy number fn_k	[−20,−20, −7,23]	[−7,23,35]	[23,35,60]	[35,60,90]	[60,90, 100,100]

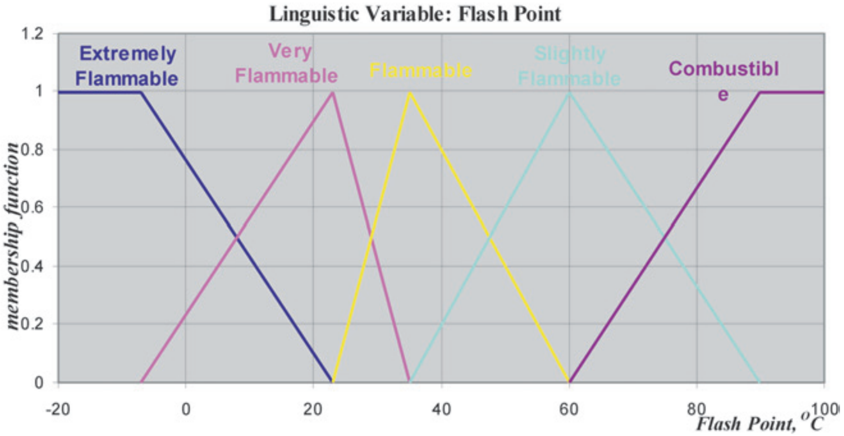

Figure 2. Fuzzy number describing the linguistic terms of the Linguistic Value 'Flash Point'

where, w_k^j is the weight factor of the k linguistic value, m_{jk}^S is the membership degree of the property value, T_j^S, for the Sth substance, and k is the kth linguistic value of the jth property.

This procedure, called 'defuzzification', results to the transformation of the membership grades to a 'normal', or crisp, number. The technique employed is called 'center-of-maximum' method[32]. It is one of the simplest, with minimum complexity in its calculations.

After calculating all penalty factors that correspond to each property value, T_j^S, that belongs to the set of values of the given property, the diagram of the 'Utility Function' can be generated. Penalty factors belong to the interval [0,1]. The Utility Function for 'Flash Point' is presented in the Figure 3. The procedure for the development of Utility Functions is in accordance he one proposed by Apostola-kis and his colleagues[72,73,74]. The above-mentioned procedure has been repeated for all the hazardous properties taken into account in the calculation of the proposed index. In cases of hazardous properties that do not have a continuous set of values, but use discreet levels or classes (e.g. reacting with water:

Table 5. Weight factors w_k, assigned to the linguistic values k of the Linguistic Variable 'Flash Point'

linguistic value, k	E.F.: Extremely Flammable	V.F.: Very Flammable	F.: Flammable	S.F.: Slightly Flammable	C.: Combustible
Weight factor, w_k	0.480	0.323	0.119	0.050	0.028

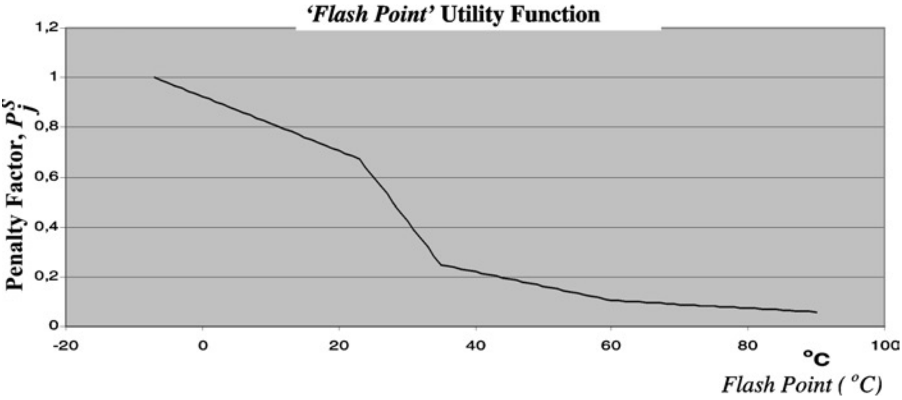

Figure 3. Utility Function for the Linguistic Value 'Flash Point'

'violently', 'reacting', 'slowly', 'not reacting'), no Utility Function can be developed. In such cases, a standard Penalty Factor was pre-assigned to each hazardous property level.

CALCULATION OF THE INDEX

The 'Substance Fire Hazard Index' for the S substance is calculated from the following equation:

$$SFHI_S = \sum_j W_j P_j^S \tag{3}$$

where, W_j is the Weight factor of the j Property, and P_j^S is the Performance measure, or Penalty factor, attributed to the jth Property for the S substance.

THE PROPOSED 'CONSEQUENCES INDEX'

The proposed 'Consequences Index' is introduced as a tool for the ranking of industrial units and installations that use, produce or store flammable and toxic substances, based on accident consequence analysis. Units and installations are classified according to the 'Consequences Potential' each one represents. As 'Consequences Potential' is defined the total of the consequences to Human Health, Environment and Property, that are possible to be caused by an accident at the installation.

The calculation of the Index is based on the 21 Consequences Categories (CCs) that have been identified. For each CC_j, a Weighting Factor, W_j, has been assigned. For the determination of the Weighting Factors, AHP has been employed. A Penalty Factor, P_{ij}, is attributed to each CC_j, for each ith installation. This factor represents the calculated, or estimated, extent of the expected possible damages from an accident at the installation, related to each CC. The assignment of these values is based either on calculation tools, or estimation. For the calculation of the Penalty Factors, a 'Utility Function', involving fuzzy sets theory and AHP, has been developed.

For the development of the Consequences Index the following steps where followed.

DETERMINATION OF CONSEQUENCES CATEGORIES, CCs

All possible consequences related to this kind of accidents were recorded and those to be incorporated in calculation of the Consequences Index, 21 in total, were determined. For their determination, a number of sources where taken into account. These include:

- Consequence Categories incorporated into other similar indices and ranking tools, for example: the MARS scale (Accident Gravity scale)[58], the 'Bradford disaster scale'[58], the 'Swiss scale'[58], and its fuzzy sets variation[58, 59, 60].
- OECD CARAT Risk Assessment Process Hierarchy. (Element I, 1.2-Identification of subjects of concern)[61].
- Consequence Categories incorporated in legislative requirements and associated technical guidance documents: E.U. 'Seveso II' Directive[62]: Guidance on the preparation of a safety report[63], MARS[64, 65] and SPIRS[66]; US EPA Risk Management Program[67]: RMP Guidance for Offsite Consequence Analysis, Chapter 11: Estimating Offsite Receptors[68].

The parameters identified and selected were classified in Consequence Categories (CCs) and then in groups and subgroups. The groups, subgroups and Categories of Consequences are presented in Figure 4 and Table 7. Consequence Categories (C.C.s), are analyzed as following.

Consequences to human health

Four population categories have been identified:

- Workers at the installation: They are aware and informed of the hazards, they are trained to respond to incidents and accidents, and they have personal protective equipment, as well as fire fighting equipment, at their disposal.
- Neighbors: not trained, but informed about what they should do in case of emergency.
- Special population categories include: children in schools, patients in hospitals, people in jails, and other sensitive population categories, around the installation. All of them are not (fully) capable of responding by themselves to an accident. They need special attention, help and resources.
- Transient population: people in recreation areas, shopping centers, sports facilities around the installation that could be affected. They are not, generally, aware of the hazards, nor trained to respond.

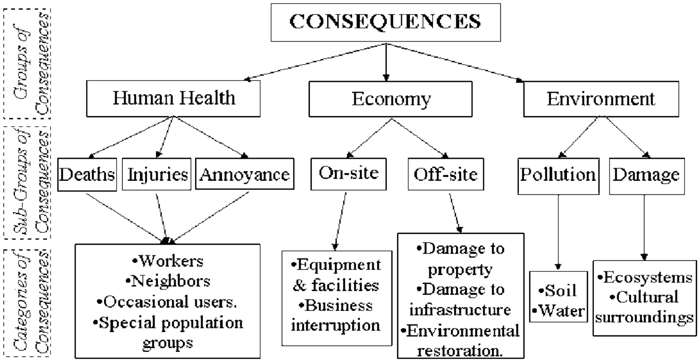

Figure 4. Hierarchical structure of the Consequences Categories

Furthermore, three undesired outcome categories for human health have been identified:

- "possible death effects": number of people inside the radius that deaths could be induced. This radius corresponds to the ERPG-3 concentration for toxic release[69], 350 mbar overpressure for explosion[70] and 1500 (TDU, 15 kw/m^2 for 40 sec exposure) for fire radiation[70].
- "possible injuries": number of people inside the radius that injuries could be induced. This radius corresponds to the ERPG-2 concentration for toxic release[69], 140 mbar overpressure for explosion[70] and 450 (TDU, 6 kw/m^2 for 40 sec exposure) for fire radiation[70].
- "possible annoyance": number of people inside the radius that slight injuries, annoyance or other slight reversible effect could be induced. This corresponds to the ERPG-1 concentration for toxic release[69], 140 mbar overpressure for explosion[70] and 170 (TDU, 3 kw/m^2 for 40 sec exposure) for fire radiation[70].

The above requirements for the overpressure and fire radiation exposure radius estimation have been set by the Greek 'Major Accidents Response Plan' (SATAME)[70]. ERPG (Emergency Response Planning Guidelines) thresholds are published by AIHA (American Industrial Hygiene Association)[71], and described in ref.[69].

The combination of the 4 population categories and the 3 effects categories provides the 12 Consequences Categories related to human health that have been incorporated in the index, and are shown of the first part (A.1–A.3) of Table 6. For the calculation of the consequences for each category, the user will have to define.

- First, the accident scenarios that will be considered.
- Next, the corresponding exposure radii for each scenario. In order to do that, some calculation tools will have to be employed. Such tools vary in requirements, precision

Table 6. Consequence Categories (CCs), their ‘value ranges’ and their weights

CCs	Description	W_j
A. Consequences to Human Health		
1. Number of people inside the ‘deaths’ radius		
A.1.a	a. Workers of the installation	0,024
A.1.b	b. Residents around the installation	0,046
A.1.c	c. Special population categories (schools, hospitals, jails around the installation)	0,11
A.1.d	d. Transient people (in recreation, shopping & sports areas)	0,363
2. Number of people inside the ‘injuries’ radius		
A.2.a	a. Workers of the installation	0,006
A.2.b	b. Residents around the installation	0,012
A.2.c	c. Special population categories (schools, hospitals, jails around the installation)	
A.2.d	d. Transient people (in recreation, shopping & sports areas)	0,095
3. Number of people inside the ‘annoyance’ radius		
A.3.a	a. Workers of the installation	0,002
A.3.b	b. Residents around the installation	0,004
A.3.c	c. Special population categories (schools, hospitals, jails around the installation)	0,009
A.3.d	d. Transient people (in recreation, shopping & sports areas)	0,031
B. Economic Consequences		
1. On-site		
B.1.a	a. Damages to machinery, installations, etc	0,007
B.1.b	b. Business Interruption	0,02
2. Off-site		
B.2.a	a. Damages to houses, other installations, etc	0,006
B.2.b	b. Damages to infrastructure	0,013
B.2.c	c. Cost of Environmental restoration	0,035
C. Environmental Consequences		
1. Pollution		
C.1.a	a. Soil	0,028
C.1.b	b. Water (lakes, rivers, shores, aquifers)	0,113
	2. Damages	
C.2.a	a. Damages to ecosystems, biotopes, protected areas, riverbanks, seashores	0,038
C.2.b	b. Damages to Cultural Assets (historical sites, cemeteries, churches, etc)	0,009

Table 7. The fuzzy classes, their weights and the fuzzy numbers that describe them

Consequences Class	C − 0	C − 1	C − 2	C − 3	C − 4
Description	"Zero"	"Small"	"Increased"	"Critical"	"Catastrophic"
Fuzzy number, fn_k	–	[0, 0.35, 0, 0.275]	[0.5, 0.65, 0.5, 0.2]	[0.75, 0.85, 0.25, 0.15]	[0.75, 0.95, 1, 1]
Weight, w_k	0	0,043	0,1312	0,3458	1

in calculations, ease of use, etc. A number of software tools have been identified, and suggested for use, some of them available through the web (such as ALOHA, RMP Comp, Archie), or used in emergency management in Greece (SATAME[70]). The user could employ any convenient and available tool, provided it is used uniformly for all installations under examination, and that its use is appropriate for the purpose. Many of these figures are actually reported under various legislative schemes (for example Seveso Safety Reports in Greece and other E.U. countries, or EPA RMP), or could be calculated from such reported data. Furthermore, the index could be modified to correspond to such data, should it be used in conjunction with any such scheme.

- Finally, the number of people for each of the 4 population categories within the 3 exposure radii is to be identified.

Economic consequences

Two economic damage sub-groups have been identified: on-site and off-site.

- Onsite damages include: property loss on the installation itself due to fire or explosion effects, as well as Business Interruption because of stopping of production. Both these categories are also incorporated in the calculation of the DOW's Fire and Explosion Index[6].
- Offsite damage include: Damage of residential and commercial property around the installation and of neighboring facilities, damages to public infrastructure: power transmission lines, communication systems, water distribution, transportation and communication systems, and civil property in general, as well as cost of restoration of possible environmental damages.

The user of the index, based on his/her experience, after taking into account the exposure radii calculated by the methods employed, will perform the estimation of the Economic Consequences and assign the appropriate values.

Environmental consequences

Two Environmental Consequences sub-groups have been identified: Pollution and Damages.

- 'Pollution' refers to possible pollution of Soil and Water bodies (lakes, rivers, seas, seashores, aquifers, etc), and
- 'Damages' are further distinguished to:
  - Damages to ecosystems, biotopes, protected areas, riverbanks, seashores, etc, and
  - Damages to Cultural Assets (historical sites, cemeteries, sacred ground, churches, etc).

The user of the index, based on his/her experience and having in mind the properties of the sub-stances involved, the conditions of the accidents scenarios and any relevant information derived from the tools employed in the previous calculations (distances to endpoints, etc), assigns to each of these four CCs a value that represents the possible extent of the consequences, either in linguistic form (e.g. "catastrophic", "small", etc) or in a relative scale from 0 to 1.

ASSIGNMENT OF WEIGHTING FACTORS W_j

For each CC_j, a Weighting Factor, W_j, is ascribed. For the determination of the Weighting Factors, Analytic Hierarchy Process is employed, as is has been described above. The implementation of AHP for the determination of the Weighting Factors, as described earlier, was based on the Hierarchical structure shown in Diagram 4. For demonstration purposes, a set of Weighting Factors to the 21 CCs of our model have been assigned (Table 6).

ASSIGNMENT OF PENALTIES P_{ij}

For each CC_j of every ith Facility, a Penalty Factor, P_{ij}, is ascribed. This Penalty Factor represents the magnitude of the calculated consequences or damages for the jth CC. The procedure for the determination of the Penalty Factors constitutes of two stages, outlined as following.

Development of "Utility Function"

The development of the Utility Function for the calculation of the Penalty Factors, P_{ij}, is based on the procedure already described in the previous section. For all of the 21 CCs, a single utility Function has been developed, in order to make calculations and the index structure simpler. For the development of the Utility Function, the CCs have been divided to 4 levels, the Consequences Classes, describing the expected intensity of an accident: 'small', 'increased', 'critical', 'catastrophic'. The fuzzy numbers describing each class have been adopted from Gheorghe et al[75]. These trapezoid fuzzy numbers, fn_k, as well as the weight factors, w_k, assigned to each one of these 'consequences classes', are presented in Table 7. These factors represent the relative weight of one class against each of the others. For the determination of the weights A.H.P. had been employed again. The weights, the linguistic description of each class, as well as the trapezoid fuzzy numbers, fn_k, that describe them are presented in Table 7.

Assignment of the ‘absolute damage measure’ T_{ij} for each CC_j

The user has to assign an input value T_{ij}, for each CC_j. This value represents the ‘absolute measure’ of the expected damage for the specific CC. For example, for the CC: “number of neighbors within the injuries radius”, the user has to calculate the relevant radius (toxic concentration based on ERPG-2 for toxic release, or overpressure for explosion, or radiation for fire). Next, the user determines the number of neighbors within that radius. For some of the CCs (e.g. those related to human health consequences), the user will have to use relevant tools for the determination of exposure radii, for other CCs, (e.g. business interruption, damages to property, ecosystems, etc); the user should assign values based on his/her own estimation. The use of specific tools in the late case, where such tools exist, could be too complicated for the calculation of an Index, and more appropriate for a detailed Safety Report or Environmental Impacts Assessment study.

CALCULATION OF THE INDEX

The “Consequences Index”, *CI*, for the ith installation is calculated from the following equation:

$$CI_i = \sum_j W_j * P_{ij} \tag{4}$$

where, W_j is the Weight Factor of the *j* Consequence Category, P_{ij} and is the Penalty for the *j* Consequence Category for the *i*th Installation.

For the calculation of the Consequences Index for the *i* facility, the next steps are followed:

(i) Assignment of an input value T_{ij}, for each CC_j.
(ii) Calculation of the Penalty value, P_{ij} are for each CC_j, using the developed Utility Function.
(iii) Introduction of the Penalty values, P_{ij}, in equation (4), from which the Consequence Index for the *i*th installation is calculated.

CONCLUSIONS

A new methodology for the development of hazard classification indices was presented in this paper. The development of the proposed methodology was based on multi-criteria decision-making, as well as on fuzzy logic. Based on the proposed methodology, two new indices, the *Substance Fire Hazard Index, SFHI*, which is focused on the major-accident hazards of the substances, as the *Consequences Index*, for the rapid ranking of Industrial Facilities that use, produce or store hazardous substances have been developed and was presented. Aim of the proposed indices is the rapid assessment and relative ranking of fire hazards and risks of chemical substances or materials and the ranking of facilities based on accident consequences potential.

For the development of the proposed methodology, the issue of hazard classification was viewed as a multi-criteria decision making problem. Therefore, a multi-criteria decision-making technique, Analytic Hierarchy Process, has been employed. As it has already been stated, AHP is capable for dealing with complex problems, involving multiples criteria of different nature, by analyzing their parameters in a hierarchical manner. On the other hand, to replace is its inability to deal with problems that cannot be represented by a strict hierarchical structure, when there are interconnections or interdependencies among parameters or elements of different subgroups of the same or different levels, an extension of AHP, the Analytic Network Process — ANP[46], has been introduced. ANP allows for feedback among different elements to be taken into account in the ranking of the alternatives. Therefore, the Hierarchical structure is transposed to a Network structure, resulting in the formation of a 'Supermatrix'. Nevertheless, the number of alternatives cannot exceed a threshold (7–9), because of the size of the 'Supermatrix' that is formed. This limitation is making ANP not suitable as a basis for the development of a generic index aiming in the classification or rapid assessment of a big, or unlimited, number of substances or installations.

Possible applications of the proposed *Substance Fire Hazard Index, SFHI*, could include:

- Tool for the rapid assessment of substances, based on their instinctive properties.
- Tool for the relative assessment of substances for the selection of a less hazardous one.
- Support tool for the substitution of a hazardous substance with a less hazardous one.
- Tool for 'risk communication' regarding the magnitude of the inherent hazard of a substance.
- Possible application fields of the "Consequences Index" could include:
- Tool for the assessment of existing installations through their relative ranking, and for focusing on installations with the bigger disaster potential.
- Tool for the assessment of proposed new installations and for the rapid ranking of alternative sites.
- Tool for the assessment of progress made at an existing installation on the reduction of its "consequences potential" (or the opposite).
- Tool for "Risk communication" regarding the magnitude of the potential impacts of an accident.

REFERENCES

1. CCPS, 1992, Guidelines for Hazard Evaluation Procedures, 2nd ed., AIChE, New York.
2. Watts, J.M., 1995, Fire Risk Ranking, in: *Handbook of Fire Protection Engineering*, SFPE/National Fire Protection Association, Quincy, MA.
3. Crawley, F. and Tyler, B., 2003, Hazard Identification Methods, EPSC/IchemE, Rugby, UK.

4. Dow, 1994, Dow's Fire & Explosion Index Hazard Classification Guide, 7th ed., AIChE, New York.
5. The Mond Index, 1993, 2nd ed., Imperial Chemical Industries, Winnington, Cheshire, UK.
6. Dow, 1994, Dow's Chemical Exposure Index Guide, AIChE, New York.
7. Tyler B.J., Thomas A.R., Doran P., Greig T., 1996, A Toxicity Hazard Index, *Chem Health Saf* 3: 19–25.
8. Scott A, 1998, Environment-accident index: validation of a model, *J Haz Mat*, 61: 305–12.
9. Stuhl D.R., 1976, Fundamentals of Fire and Explosion, AIChE.
10. Kahn, F.I. and Abbasi, S.A., 1998, Multivariate Hazard Identification and Ranking System, *Proc Saf Progr*, 17: 3, 157–70
11. Khan, F.I., Husain, T. and Abbasi S.A., 2001, Safety Weighted Hazard Index (SWeHI): A New, User-friendly Tool for Swift yet Comprehensive Hazard Identification and Safety Evaluation in Chemical Process Industries, *Proc Saf Env Prot*, 79: 2: 65–80.
12. Kahn, F.I. and Abbasi, S.A., 1997, Accident Hazard Index: A Multi-attribute Method for Process Industry Hazard Rating, *Proc Saf Env Prot*, 75: 4: 217–224.
13. Shah, S., Fischer U. and Hungerbühler, K. 2003, A Hierarchical Approach for the Evaluation of Chemical Process Aspects From the Perspective of Inherent Safety, *Proc Saf Env Prot*, 81: 430–443.
14. Gentile, M., Rogers, W.J., and Mannan, M.S. 2003, Development of a Fuzzy Logic-based Inherent Safety Index, *Proc Saf Env Prot*, 81: 444–456.
15. Gunasekera, M.Y. and Edwards, D.W., 2003, Estimating the Environmental Impact of Catastrophic Chemical Releases to the Atmosphere. An Index Method for Ranking Alternative Chemical Process Routes, *Proc Saf Env Prot*, 81: 463–474.
16. Tixier, J., Dusserre, G., Salvi, O. and Gaston, D., 2002, Review of 62 risk analysis methodologies of industrial plants, *J Loss Prev Proc Ind*, 15: 291–303.
17. NFPA 325, 1994, *Guide to Fire Hazard Properties of Flammable Liquids, Gases and Volatile Solids*, 1994 edition, National Fire Protection Association, Quincy, MA.
18. Lees, F.P., 1996, *Loss Prevention in the Process Industries*, Butterworth-Heinemann, Oxford.
19. NFPA 49, *Hazardous Chemicals Data*, 1994 ed., National Fire Protection Association, Quincy, MA
20. CCPS, 1996, *Guidelines for Engineering Design for Process Safety*, AIChE, New York.
21. Saaty T.L, 1980, *The Analytic Hierarchy Process*, McGraw Hill, New York.
22. Zadeh, L., 1965, Fuzzy sets, *Information and Control*, 8: 338–353.
23. Yager R.R., S. Ovchinnikov, R.M. Tong and H.T. Nguyen, (Editors) (1987). *L.A. Zadeh: Selected Papers on Fuzzy Sets and Applications.* John Wiley & Sons, New York.
24. Kim, C.E., Ju, Y.J., and M. Gens, 1996, Multilevel fault tree analysis using fuzzy numbers. *Com Oper Res*, 23: 695–703.
25. Kraslawski A. and L. Nystr*o*m, 1995, Fuzzy index for the estimation of product and process toxicity, *Chem Eng Proc* 34: 433–437.
26. Pelaez E. and Bowles J., 1996, Using Fuzzy Cognitive Maps as a System Model for Failure Modes and Effects Analysis. *Information Sciences*, 88, 1–4, pp. 177–199.

27. Wang X.Z., Yang A., Yang H. and McGreavy C., 1996, The application of fuzzy qualitative simulation in safety and operability assessment of process plants. *Comp Chem Eng*, 20: S671–6.
28. Wang X.Z., Chen H., Yang H. and McGreavy C., 1996, Neural nets, fuzzy sets and digraphs in safety and operability studies of refinery reaction processes. *Chem Eng Sci*, 51: 2169–2178.
29. Lin C.T. and M.J. Wang, 1997, Hybrid fault tree analysis using fuzzy sets, *Rel Eng Syst Saf*, 58: 205–213.
30. Singer D., 1990, Fault tree analysis based on fuzzy logic. *Comp Chem Eng* 14: 259–266.
31. Bonvicini S., P. Leonelli and G. Spadoni, 1998, Risk analysis of hazardous materials transportation: evaluating uncertainty by means of fuzzy logic, *J Haz Mat*, 62: 1, pp. 59–74.
32. Klir G.J, Yuan B., 1995, Fuzzy sets and fuzzy logic, Prentice Hall.
33. Zimmerman, H.J., 1996, *Fuzzy set theory and its applications*, 3rd ed. Kluwer Academic Publishers, Boston.
34. Kosko B., 1997, *Fuzzy Engineering*. Prentice-Hall, Upper Saddle River, NJ.
35. Yen J. and Langari R., 1999, *Fuzzy Logic: Intelligence, Control, and Information.* Prentice-Hall, Upper Saddle River, NJ.
36. NFPA 704, 1996, *Standard System for the Identification of the Hazards of Materials for Emergency Response*, 1996 edition, National Fire Protection Association, Quincy, MA.
37. CCPS, 1996, Inherent Safer Chemical Processes: A Life Cycle Approach, AIChE, New York.
38. Hendershot, D.C., 1997, Inherently safer chemical process design, *J Loss Prev Proc Ind*, 10: 151–157.
39. http://www.expertchoice.com/hierarchon/subjects.htm
40. Anderson D.R, Sweeney D.J., Williams T.A., 1991, An introduction to management science: quantitative approaches to decision making. 6th ed., West Publishing, St. Paul, Minn.
41. Shields J. and G. Silcock, 1986, An apllication of the Hierarchical Approach to Fire Safety, *Fire Saf J*, 11: 235–242.
42. Dodd F.J and H.A. Donegan, 1994, Prioritisation Methodologies in Fire Safety Evaluation, *Fire Technology*, Sencond Quarter 1994, pp. 232–249.
43. Dodd F.J and H.A. Donegan, 1994, Some considerations in the combination and use of expert opinions in Fire Safety Evaluation, *Fire Saf J*, 22: 315–327.
44. Yeo S. H., and Neo, K.G., (1998, Inclusion of environmental performance for decision making of welding processes, Journal of Materials Processing Technology, 82: 78–88.
45. Cagno E., Caro F., Mancini M. and Ruggeri F., 2000, Using AHP in determining the prior distributions on gas pipeline failures in a robust Bayesian approach, *Reliab Engn Syst Saf*, 67: 275–284.
46. Saaty, T.L, 1996, The Analytic Network Process: Decision Making With Dependence And Feedback. RWS Publications, Pittsburgh, PA.
47. ILO, 2001, *Globally Harmonized System for the Classification and Labeling of Chemicals-GHS*, International Labor Organization, http://www.ilo.org/public/english/protection/safework/ghs/ghsfinal/index.htm.

48. DOT, 2001, Hazardous Materials Regulations, Title 49 CFR, U.S. Department of Transportation.
49. European Commission, 1996, Council Directive 96/82/EC "on the control of major-accident hazards", (OJ No L 10 of 14 January 1997).
50. NFPA 30, 1996, *Flammable and Combustible Liquids Code*, 1996 edition, National Fire Protection Association, Quincy, MA.
51. Federal Emergency Management Agency, U.S. Department of Transportation, and U.S. Environmental Protection Agency, 1988, Handbook of chemical hazard analysis procedures. Washington, D.C.: Federal Emergency Management Agency Publications Office.
52. Suarez and Kirchsteiger, C., 1998, A Qualitative Model to Evaluate the Risk Potential of Major Hazardous Industrial Plants, European Commission, Joint Research Center, Major Accident Hazards Bureau, Ispra.
53. Ludwig, T. 1991, Industrial Fire Prevention and Protection, Van Nostrand Reinhold, N.York.
54. Tuhtar, D., 1989, Fire and Explosion Protection: A Systems Approach, Horwood E.
55. Drysdale. D., 1999, Introduction to Fire Dynamics, 2nd ed., John Wiley and Sons, Chichester.
56. Crowl, D., Louvar, J., 1990, Chemical Process Safety-Fundamental with Applications, Prentice-Hall, N.Jersey.
57. Expert Choice Inc, 2000, Expert Choice 2000: Quick start guide & tutorials, Expert Choice Inc, Pittsburgh, PA.
58. Kirchsteiger, C., 1998, Absolute and relative ranking approaches for comparing and communicating industrial accidents, *J Haz Mat*, 59: 31–54.
59. Wyler, E., Bohnenblust, H., 1991, Disaster scaling — a multi-attribute approach based on fuzzy sets theory, in: Apostolakis, G. (ed.) Probabilistic Safety Assessment and Management, Elsevier, Amsterdam, 1991.
60. Christen, P., Bohnenblust, H. and S. Seitz, 1994, A methodology for Assessing Catastrophic Damage to the Population and Environment: A quantitative multi-attribute approach for Risk Analysis Based on Fuzzy Sets Theory, *Proc Saf Prog* 13: 234–238.
61. OECD, 2000, http://www.oecd.ogr/EHS/CARAT/v3.0/htm/home/hierarchy.htm
62. European Commission, 1996, Council Directive 96/82/EC "on the control of major-accident hazards", (OJ No L 10 of 14 January 1997).
63. Papadakis, G.A., Amendola, A., 1997, Guidance on the preparation of a safety report to meet the requirements of Council Directive 96/82/EC (Seveso II), European Commission, DG JRC, EUR 17690 EN, Luxembourg: Office for Official Publications of the European Communities.
64. Kirchsteiger, C., 2001, Technical Guideline on Reporting Accidents to the MARS Database. European Commission, DG JRC, EUR 19768, Ispra.
65. Kirchsteiger, C., 2001, MARS 4.0 – An Electronic Documentation & Analysis System for Industrial Accidents Data – User's Manual, European Commission, DG JRC, EUR 19766 EN, Ispra.

66. Kirchsteiger, C., 2001, SPIRS 2.0 – An Electronic Documentation & Analysis System for Industrial establishments Data, User's Manual. European Commission, DG JRC, EUR 19767 EN, Ispra.
67. U.S.Federal Register, 1996, 40 CFR Part 68, Accidental Release Prevention Requirements: Risk Management Programs Under the Clean Air Act, Section 112(r)(7); List of Regulated Substances and Thresholds for Accidental Release Prevention, Stay of Effectiveness; and Accidental Release Prevention Requirements: Risk Management Programs Under Section 112(r)(7) of the Clean Air Act as Amended, Guidelines; Final Rules and Notice, 61 FR 31668, June 20, 1996.
68. U.S. Environmental Protection Agency, 1999, Risk Management Program Guidance for Offsite Consequence Analysis, EPA 550-B-99-009.
69. American Industrial Hygiene Association, 1998, Emergency Response Planning Guidelines,AHIA,Akron,OH
70. Markatos, N.C., Kyranoudis, C.T., Zografos, K., Ziomas, I., 1999, An operational center for managing major chemical industrial accidents, in Seveso 2000 Conf., Nov. 10–12, Athens, pp. 282–291, http://mahbsrv.jrc.it/Proceedings/Greece-Nov-1999/I2-KYRANOUDIS-z.pdf.
71. http://www.aiha.org/
72. Bonano, E.J., Apostolakis, G.E., Salter, P.F., Ghassemi, A., Jennings, S., 2000, Application of risk assessment and decision analysis to the evaluation, ranking and selection of environmental remediation alternatives, *J Haz Mat.*, 71: 35–57.
73. Accorsi, R., Apostolakis, G.E., Zio, E., 1999, Prioritizing stakeholder concerns in environmental risk management, *J Risk Res.*, 2:11–29.
74. Accorsi, R., Zio, E., Apostolakis, G.E., 1999, Developing Utility Functions for Environmental Decision Making, *Prog Nucl Energy*, 34: 387–411.
75. Gheorghe A.V., Mock R. and Kroger, 2000, Risk Assessment of regional systems, *Rel Eng Syst Saf*, 70: 141–156.
76. Marshall, J., Mundt, A., 1995, The Relative Risk of Pressurized and Refrigerated Storage for Six Chemicals, *Proc Saf Prog*, 14: 200–211.