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Fire & Explosion Risk Assessment: Application to the Fine Chemicals Industry

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The “so-called” Seveso III directive (Directive 2012/18/EU) impose to plant managers to perform a detailed risk assessment and to adopt adequate protection measures in the case their facility is included among those considered subjected to Major Accident, i.e., if the amount of hazardous substances stocked and handled within it is superior to defined threshold limits. Fire risk evaluation needs to consider each plant's complexity and the different regulations and codes it is subjected to. Meanwhile, a thorough approach is required, which does not base itself uniquely on qualitative methods (such as checklists) or semi-quantitative (such as fire load-based approach) but should consider these latter as starting processes to develop a more comprehensive evaluation. Besides this, accident scenarios associated with chemical plants may differ significantly, according to the substances handled, the activities and processes implemented: typically, they could range from small to medium scale in terms of consequences, depending on the impact on human operators and structures. Several “risk screening” methods exist, differing from their fields of applications and limitations, as detailed by Danzi et al. (2018). The SW&HI methodology was developed by Khan et al. (2001). It is a fast tool that allows to identify the most hazardous units in chemical process plants, underline the criticalities associated with different substances, processes, and operations, evaluate the effectiveness of the protection measures in place, compare the risk level attributed to different chemical processes, define the adequate additional measures to reduce the risk to an acceptable level. In this work, the SW&HI method (with the modifications proposed in Danzi et al. 2018) is adopted as a preliminary risk screening approach in the production departments of a fine chemicals production plant in Northern Italy, which is identified as a relevant case study due to the heterogeneity of substances and chemical processes available. This study aims to verify the applicability and effectiveness of SW&HI when adopted in the evaluation of fire risk of "medium-size” plants, or “just below” Seveso III thresholds facilities (which could be considered as a majority in Italy), and to identify the prevention and protection measures most suitable to be implemented in this context to mitigate the fire and explosion scenario. The risk assessment conducted in this work will contribute, with further applications, to: (a) the tuning and calibration of the SW&HI method to "medium" scale chemical industrial realities; (b) the definition of a standard procedure of fire and explosion risk screening through SW&HI; (c) the implementation of the validated method into the Italian fire risk regulations.
Keywords: fire risk analysis, index method, chemical industry

1. Introduction

Chemical plants are complex environments where potential hazardous material and processes are often present. Work-owners must consider the risks related to substances and process conditions and individuate potential accident scenario and consequences as to grant working activities are performed in safe and secure ambiances to safeguard operators’ life and environment.
The principal methodologies to be compliant with the Seveso III directive are 30 years old (the first dated back to 1980) and updated in the early ’90s. Their development derives from the need for insurance companies to evaluate adequate insurance fees quickly. The most used are the Dow F&EI (Dow, 1987, AICHE 1994) and the Mond Index methods (ICI, 1985), both thought to be explicitly applied to the oil & gas industry. In the years, many researchers proposed methods to assess chemical plants' inherent safety through various ways

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of indexing the hazard potential and the related risk. Among these, relevant is the contribution by Khan and co-workers who developed integrated inherently safety indexing methods (Khan and Amyotte, 2004, 2005) and by Heikkila, who introduced the use of inherent safety indices. Generally speaking, these methods are not suited for all those facilities where a relatively low amount of substances is present, the threshold limits are defined as for Dow F&EI method (Dow, 1987) as 5000 lb. (or 600 gal) of flammable substances, while Seveso III directive adopts threshold values accordingly to the type of substances. All plants below the threshold are not considered “subjected to major accidents, though fire and explosion risk could be high if work-owners and regulations impose any prevention/protection strategies; besides this, the cited methods lack in some aspect of the risk classification strategy (see Danzi et al. 2018).
To this purpose, indexing methods could be employed: they are devoted to risk evaluation screening procedures, as their application is quick and cost-saving, and potential critical issues could be quickly underlined (Danzi et al. 2020).
Among the most recent, the HIRA method (Khan and Abbasi, 1998), RRHI (Kao and Duh, 1998), and SW&HI method Khan et al., 2011). The latter was adopted in this work and applied to a fine chemicals industry in Northern Italy as a test case.
The approach followed here is intended to incorporate an international validated method (SW&HI, Khan et al., 2001) and the Italian regulations currently in law in the fire safety field.
The process department of a chemical plant that is subjected to Seveso III could be evaluated according to this EU Directive regulations, while the SW&HI method could help to evaluate whether a processing unit does represent a “specific risk” or not. In this approach, SW&HI is used as a preliminary screening tool: once identified the units at risk, these must be further evaluated with a more detailed approach (such as CFD simulations) to assess the likelihood of accident scenarios and their magnitude consequences. Figure 1 reports the approach adopted in this work to assess the most hazardous units in the case study. A threshold value of the SW&HI index has been adopted: units with an index smaller than 5, which associate with a Light to Low risk in the method logic, are considered “reasonably acceptable,” and no additional measures are requested. On the other side, units with greater than 5 values are considered at “specific risk,” and mitigation measures, in the form of additional credits according to the SW&HI methodology, are introduced to lower the risk to an acceptable level.

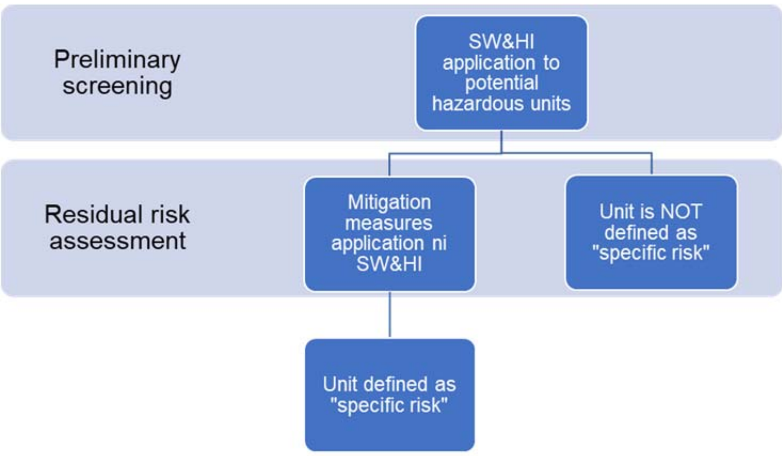

Figure 1: This work’s approach to screen “specific” risk process units

2. SW&HI method

The SW&HI (Safety Weighted Hazard Index) method has been developed by Khan et al. (2001) as a quick and user-friendly tool for identifying hazards and assessing fire and explosion risk in the process industry. It represents an evolution of a previous method developed by the same authors (HIRA, 1998). The authors intended to create a more systematic tool that provides an evaluation procedure to the user more comprehensible and reproducible than previous methodologies.
The SW&HI method allows defining a risk level index, called SWEH Index, which represents, in quantitative terms, the radius of the area in which there are conditions of moderate danger or where there is a probability of fatality/damage equal to 50 %. The index is assessed by considering all existing control and protection measures; the higher the index's value, the more vulnerable the unit analyzed will be.
The index is evaluated as:

$$SWEHI = {}^{B}/_{A} \quad (1)$$

Where B represents the quantitative measure of the damage caused by the process unit on an area that considers 50% of the probability of damage (m^2), and A represents the sum of the credits attributed to the installed protection systems.
Each unit must tend towards an SW&HI value as small as possible, and this objective can be pursued either by reducing the value of B or increasing value A, i.e., mitigating the risks due to hazardous substances or processes adopting better prevention and protection measures.
Plant units are classified into 5 macro-categories, depending on operations performed (storage, chemical reactions, handling of materials, physical operations etc.). A different logical flow for index evaluation is associated with different units: weighted factors allow the procedure to be as more specific as possible to consider all unit peculiarities and critical points.
In this work, only term B1 (fire and explosion risk) is evaluated, which depends on different factors (process conditions and type of substances mainly), grouped within the definition of “Hazard potential”.
The A value includes factors defined as "credits", depending on the company's safety management, the effective presence of control systems and failure prevention, protection devices, the characteristic of operators and operation, the reliability of equipment, etc.

3. Case study

As a case study, the plant produces chemicals for polymers, cosmetics, and other manufacturing sectors, with different dedicated production lines.
Process equipment studied are essentially reactors and auxiliary equipment. The chemical processes include esterification, ethoxylation, mixing.
The units analyzed are located in three departments, devoted to different production lines, identified as departments A, B, and C.
Main units represented in these areas are reactors, storage tanks, intermediary tanks, distillation columns, heat exchangers, and other ancillary equipment serving the different production lines; most of the processes are batch, reactants are charged with dedicated lines from supply tanks or trucks, after inerting with a nitrogen purge.

Table 1: Overview of hazardous substances handled in the plant

Department	Key Substance	Classification	The total amount in the plant (Tonn)	N° of units
A	Ethylene oxide	P2	25	10
B	Methanol	P5a	55	12
	n-Heptane	P5a	40	26
	Hydrogen	P2	0.01	2
C	Toluene	P5a	8.5	18
	n-Heptane	P5a	40	21
	Methanol	P5a	55	6

Table 1 reports the main hazardous substances present in the departments, in particular: Ethylene oxide is stored in several tanks, and it is used in ethoxylation reactors; Methanol is mostly a by-product of process reactions; n-Heptane and Toluene are used as the solvent medium in different reactors; Hydrogen is fed to a hydrogenation reactor from a dedicated pipeline coming from outside the plant.
The most hazardous units are identified in the Safety report of the plant society as the followings:

- • N-heptane recovery units (C2, C5, C7, C8);
- • N-heptane intermediate and process tanks (B15, B36);
- • N-heptane charging line into reactors (B14, C1, C, C4, C6)

SW&HI index incorporates several factors, mostly related to the key substance identified in the unit. “Energetic factors” are defined depending on the substance properties which could enhance or reduce fire hazards, such as Flash Point, Vapor Pressure, Heat of combustion. These values are compared with the actual process conditions to identify whether a potentially flammable atmosphere could arise. The heat of combustion has a relevant impact on the SW&HI index. Figure 2 shows the SW&HI index calculated at the same units when different chemicals are handled (N-heptane and Toluene).
The higher value is obtained at unit C5 when handling N-heptane due to its high combustion heat and greater inventory (almost double than the others, as C5 is a storage tank).

An experience-based hypothesis (drawn by other similar applications, such as Danzi et al., 2018) set the acceptable risk index threshold to 5. Detailed analysis must be undertaken for any units with a higher value to determine why the equipment safety is compromised and which protection/prevention measures are required. As they are identified and applied, the SWEHI index will be recalculated.

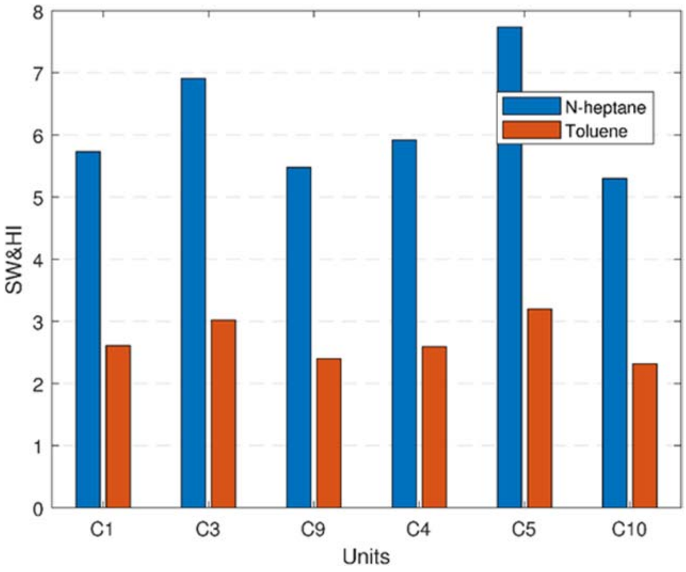

Figure 2: Effect of type of substance (heat of combustion) on SWEHI index in different volume units.

4. Results and discussion

Figure 3 shows how the adopting of protection and mitigation measures influence the SW&HI index. In this case, additional improved flow and level control systems are implemented. In this way, the index cr_4 of the method increases. A high level of risk is still computed in the case of storage tank loading operations, while the risk of other process phases reduces below the acceptable threshold.

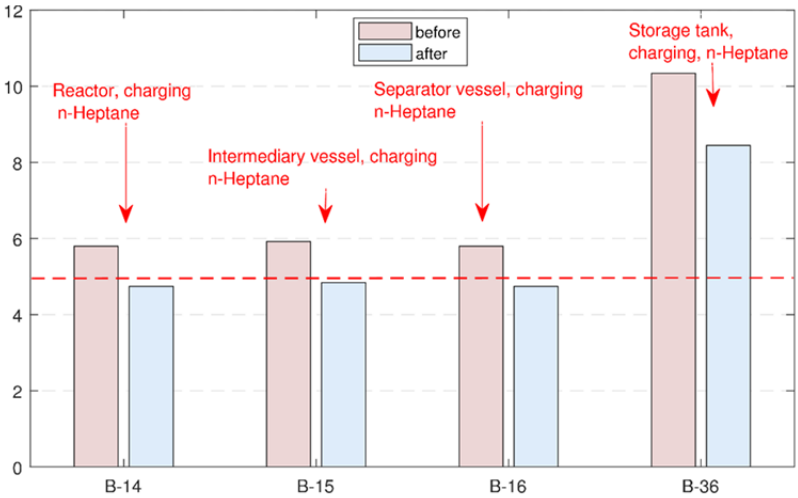

Figure 3: Hazardous units in department B, SWEHI index before and after control system improvement.

The unique solution to mitigate the latter is to reduce the hold-up of the tank or by implementing advanced improved system controls and fire safety measures such as an improved control system (on other process variables), a higher degree of automatization of operations (degree of human-machine interaction is lowered, e.g., with a dedicated feeding line from storage tanks to reactors), with additional fire protection devices (flame arrestors, water blankets, inert gas sprinklers).

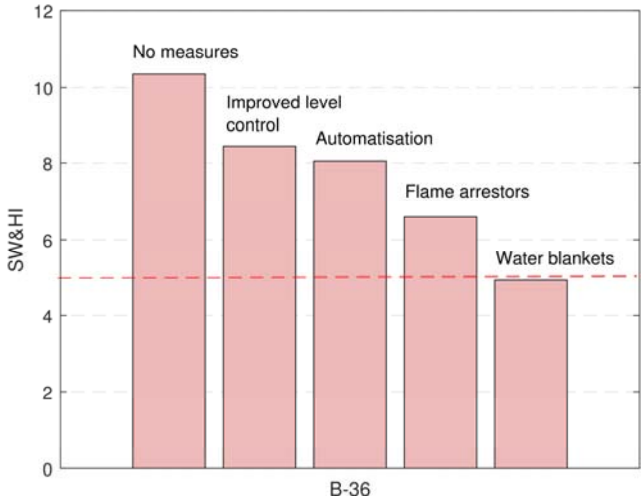

Figure 4: Effect of additional fire safety measures on N-heptane storage tank unit.

Reducing the mass amount of N-heptane in the tank, without any other additional measures, would lower the SW&HI below 5, only if the tank is emptied for more than one-fourth of its hold-up, which is unpracticable for production yield reasons. According to the SW&HI results, further measures have to be taken into account to meet the acceptability criteria according to the SW&HI method (Figure 4).

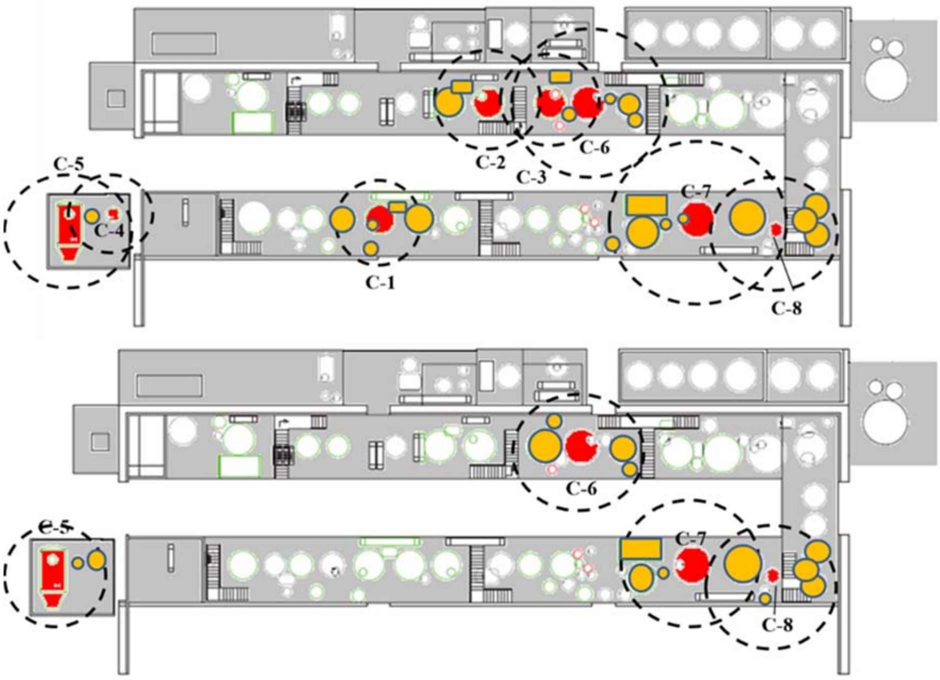

Figure 5: Graphical representation of SW&HI damage area, before (top) and after (bottom) implementation of control measures, in department C (units containing flammables with greater than 5 SW&HI are depicted in red, others in yellow)

Figure 5 reports the SWEHI index representation in department C of the plant, respectively, before and after implementing the additional credits method due to improved control systems on the units.

As the SWEHI value is pictured as a damage radius, the additional measures' effect could be better appreciated. The radius is decreased in size with respect to “no measures” configuration, potential hazards from multiple items involved scenario (domino effect) is almost prevented, since total equipment included in the damaged area is reduced, while also no domino effects will be expected on other “greater than 5 SWEHI” units in the after configuration. Units C1, C2, and C3 are downgraded to a Low-risk level (smaller than 5) following the inclusion of safety measures.

5. Conclusions

SW&HI method is applied thoroughly on the totality of the units present in the chemical plant test case. A comparable result is found with respect to the detailed analysis performed to comply with the “Seveso III” legislation: both applications identify the same units as the most hazardous in the site. The method also allows to integrate additional measures and verify their effectiveness: in this case, implementing an improved control system can lower the risk level. Domino effect could also be assessed with the adoption of SWEHI graphic representation, and damage radius could be compared to identify the involved units according to the scenario.
The method could hence be adopted as a screening tool when the fire & explosion risk of a “subject to major accident” plant must be assessed (according to EU legislation) and to exclude from further less cost-effective investigations units that are classified as not “specific” risk, or with a SW&HI index lower than a predefined threshold. In this case, a value equal to 5 applied adequately, while other chemical industrial sectors, with different substances and processes, may need to better tune the threshold risk level for acceptability.

References

American Institute of Chemical Engineering, 1994. Engineering. Dow’s Fire&Explosion Index Hazard Classification Guide.

Amyotte, P. R., Berger, S., Edwards, D. W., Gupta, J. P., Hendershot, D. C., Khan, F. I., Mannan S., Willey, R. J. (2016). Why major accidents are still occurring. Current Opinion in Chemical Engineering: 14, 1–8.

C. S. Kao, Y. S. Duh. Chemical runaway reaction hazard index and risk assessment. In proceeding from 9th International Symposium Loss Prevention and Safety Promotion in the Process Industries, 965-975, 1998

Danzi, E., Bergamo, G., Fiorentini, L. & Marmo L. (2018). Development and Application of Fire & Explosion Risk Index Methods to Chemical Process Plants. Chemical Engineering Transactions: 67, 217-222

Danzi, E., Fiorentini, L., & Marmo, L. (2020). FLAME: A Parametric Fire Risk Assessment Method Supporting Performance Based Approaches. Fire Technology.

Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC (OJ L 197/1 24.07.2012)

Dow Chemical Company, Fire & explosion index DOW (F&EI), 6Th Edition, AIChE, 1987

Heikkila, A., 1999. Inherent Safety in Process Plant Design: An Index-Based Approach [Espoo, Finland. Helsinki University of Technology.

Imperial Chemical Industries (ICI), The Mond Index, Second Edition. 1985.

Khan, F.I., Amyotte, P.R., 2004. Integrated inherent safety index (I2SI): a tool for inherent safety evaluation. Process Saf. Prog. 23, 136–148.

Khan, F.I., Amyotte, P.R., 2005. I2SI: a comprehensive quantitative tool for inherent safety and cost evaluation. J. Loss Prev. Proc. 18, 310–326.

Khan, F. I. and Abbasi, S. A., 1998, Multivariate hazard identification and ranking system, Process Safety Progress, 17(3): 157-165

Khan, F. I., Husain, T., & 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. Process Safety and Environmental Protection, 79(2), 65–80.