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Safety assessment in plant layout design using indexing approach: Implementing inherent safety perspective
Part 2—Domino Hazard Index and case study

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ABSTRACT

The design of layout plans requires adequate assessment tools for the quantification of safety performance. The general focus of the present work is to introduce an inherent safety perspective at different points of the layout design process. In particular, index approaches for safety assessment and decision-making in the early stages of layout design are developed and discussed in this two-part contribution. Part 1 (accompanying paper) of the current work presents an integrated index approach for safety assessment of early plant layout. In the present paper (Part 2), an index for evaluation of the hazard related to the potential of domino effects is developed. The index considers the actual consequences of possible escalation scenarios and scores or ranks the subsequent accident propagation potential. The effects of inherent and passive protection measures are also assessed. The result is a rapid quantification of domino hazard potential that can provide substantial support for choices in the early stages of layout design. Additionally, a case study concerning selection among various layout options is presented and analyzed. The case study demonstrates the use and applicability of the indices developed in both parts of the current work and highlights the value of introducing inherent safety features early in layout design.

1. Introduction

The present paper is Part 2 of a research effort aimed at implementing an inherent safety perspective within the early stages of layout design. In Part 1 (accompanying paper), the main focus was on the use of inherent safety guidewords and the development of a safety assessment tool for early layout analysis. The hazard of domino escalation was identified as a critical element for consideration during such analysis. Additionally, a reference index able to quantify the domino hazard was identified as being essential to reduce subjectivity and to support the assessment of design options. Thus, in the current paper (Part 2) a purpose-developed reference index, termed the Domino Hazard Index (DHI), is introduced. For each unit, this index considers the actual consequences of possible escalation scenarios and scores or ranks the accident propagation potential. The contributions of inherent and passive protection measures are assessed in the score attribution.

Section 3 of the current paper presents a case study concerned with the selection of plot options on the basis of the inherent safety criteria identified in Part 1 (accompanying paper). The indexing approaches introduced in both Part 1 and Part 2 are applied and demonstrated in the case study.

2. Domino Hazard Index

The Domino Hazard Index is specifically aimed at assessing the domino effect hazards caused by a unit in a specific layout. The index is able to consider the effects of both inherent and passive measures on the domino escalation potential. The specific use of the index as a reference within the framework of I2SI for layout assessment decides whether to account for the effects of passive measures in the DHI calculation. (I2SI is the overall Integrated Inherent Safety Index as described in the accompanying Part 1 paper.)

Fig. 1 illustrates the assessment procedure for the Domino Hazard Index. Table 1 summarizes the definition and range of the main indices of the procedure. The starting point is the plant layout plan, from which the relative distances of the geometric centres of each possible pair of units are evaluated. The distances can be arranged for ease of use in a matrix form ($D_{i,k}$). In subsequent steps of the

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Nomenclature

$C_{\mathrm{ConvSafety}}$	cost of conventional safety ($)
$C_{\mathrm{InhSafety}}$	overall cost of safety with inherent safety implementation ($)
C_{Loss}	value of expected loss ($)
CSCI	Conventional Safety Cost Index
d_{b}	distance from explosion source where overpressure effect is of concern (m)
d_{e}	distance of explosion source from centre of primary unit (m)
d_{f}	spatial dimension occupied by flame envelope (m)
d_{r}	spatial dimension affected by radiation from flame envelope (m)
d_{s}	characteristic dimension of secondary unit on the layout plan (m)
$D_{i,k}$	geometric distance between *i*-th unit and *k*-th unit (m)
DHI	Domino Hazard Index
DHS	Domino Hazard Score
$\mathrm{DHS}_{i,k}$	maximum Domino Hazard Score for escalation from *i*-th to *k*-th unit
$\mathrm{DHS}_{i,k,h}$	Domino Hazard Score for *h*-th propagation scenario from *i*-th to *k*-th unit
DI	Damage Index
HCI	Hazard Control Index
HI	Hazard Index
I2SI	Integrated Inherent Safety Index
ISCI	Inherent Safety Cost Index
ISI	Inherent Safety Index
$\mathrm{ISI_a}$	Inherent Safety Index for guideword attenuation
$\mathrm{ISI_l}$	Inherent Safety Index for guideword limitation of effects
$\mathrm{ISI_{la}}$	Inherent Safety Index for guideword limitation of the affected area
$\mathrm{ISI_{lb}}$	Inherent Safety Index for guideword limitation of the damage potential to target buildings
$\mathrm{ISI_{le}}$	Inherent Safety Index for guideword limitation of the effects of domino escalation
$\mathrm{ISI_{si}}$	Inherent Safety Index for guideword simplification
ISPI	Inherent Safety Potential Index
LSI	Loss Saving Index
PHCI	Process and Hazard Control Index
SWeHI	Safety Weighted Hazard Index
ζ	cutoff value for DI in domino escalation analysis

procedure, each single unit is analyzed, with the ultimate goal being to evaluate the DHI_i for a particular unit.

The primary accidental events that may result in domino effects arising from the assessed unit (*i*-th unit) must be identified. These events depend on the chemical characteristics, inventory and operating conditions relevant to the primary unit. Methods for primary event identification are widely available in literature (e.g. [1,2]). Table 2 provides an overview of the possible primary events which can trigger domino effects. Table 3 classifies the accidental events according to the involved escalation vector (i.e. the physical phenomenon that causes the escalation from one unit to another).

Each possible pair of units (‘*i*’ being the assessed primary unit and ‘*k*’ the secondary unit) that can potentially result in a domino escalation scenario is analyzed. A selection criterion is defined in order to account only for the units that have significant potential for an increase in accidental adverse consequences, or that are considered highly hazardous ‘per se’. The Damage Index (DI) of the original I2SI approach [3] is used as the hazard indicator for the units in this procedure (Eq. (1)):

$$\begin{aligned}&\text{If}\quad \mathrm{DI}_k > (\min(\mathrm{DI}_i;\zeta))\quad \text{then}\\ &\quad k\text{-th unit is assessed as secondary unit}\\ &\quad \text{else } k\text{-th unit is skipped (gives only minor consequences)}\end{aligned} \tag{1}$$

where ζ is an arbitrary threshold value that defines the lower limit of DI for units considered highly hazardous ‘per se’; in the Section 3 case study, ζ is taken as having a value of 25.

For each identified primary accidental event (*h*-th event) for the assessed unit (*i*-th unit), a Domino Hazard Score ($\mathrm{DHS}_{i,k,h}$) is evaluated for each of the secondary targets (*k*-th unit). $\mathrm{DHS}_{i,k,h}$ is therefore a ranking that represents the score given to the hazard in terms of an escalation from unit ‘*i*’ to unit ‘*k*’ by event ‘*h*’. The maximum value for DHS is 10, meaning that escalation is highly probable; the minimum value, 0, represents the inherently ‘safest’ level for domino escalation (i.e. elimination of the escalation hazard). The value of $\mathrm{DHS}_{i,k,h}$ for each possible event is derived by comparison of the physical effect distances associated with that particular event to the actual distance between units on the layout plan. The rules for assigning $\mathrm{DHS}_{i,k,h}$ values are summarized in Table 4 and are discussed in detail in Sections 2.1–2.4.

Once the $\mathrm{DHS}_{i,k,h}$ values have been assessed, the worst possible scenario is selected as a reference among all the possible scenarios, yielding $\mathrm{DHS}_{i,k}$ for every pair of considered units (Eq. (2)):

$$\mathrm{DHS}_{i,k} = \max_h(\mathrm{DHS}_{i,k,h}) \tag{2}$$

where subscript *h* identifies the scenario.

The final index (DHI_i) for the *i*-th primary unit is the sum of the scores ($\mathrm{DHS}_{i,k}$) for all possible secondary target units (Eq. (3)):

$$\mathrm{DHI}_i = \sum_k \mathrm{DHS}_{i,k} \tag{3}$$

An upper limiting value of 100 is imposed on DHI_i for practical applications.

The rules for assigning $\mathrm{DHS}_{i,k,h}$ values are now presented according to the classification of escalation vectors given in Table 3.

2.1. Flame impingement/heat radiation

Fire could cause escalation due to equipment overheating (by direct flame impingement or by far-field heat radiation effects from the flame surface), or due to direct ignition of flammable vapors. Different fire scenarios therefore need to be analyzed in detail, as each scenario would have different flame properties and heat loads—thus influencing the escalation mechanism.

2.1.1. Short duration scenarios

In short duration scenarios (i.e. flash fire and the thermal effects associated with vapor cloud explosions, VCEs), escalation is likely to occur only by direct ignition of flammable vapors ([4,5] and references cited therein). Thus, only secondary units likely to release vapors (e.g. a floating-roof tank) are considered in the analysis. Affected secondary units within a distance ($D_{i,k}$) that can possibly be reached by the flame, receive a score of $\mathrm{DHS}_{i,k,h} = 10$; otherwise $\mathrm{DHS}_{i,k,h} = 0$. In usual industrial practice, passive measures are not considered to be effective in limiting this mode of escalation.

Fireballs involve high thermal radiation levels in the area occupied by the flames, even if the duration of the event is short. Previous work concerning escalation likelihood has shown that escalation is reasonably possible only for impinged atmospheric vessels, while pressurized vessels are generally unaffected. Moreover, escalation phenomena are unlikely to occur for radiation from a distant source without impingement ([4–6] and references cited therein). The fireball radius (d_{f}) is the key dimension for evaluation of escalation possibility. Thus, the presence of an atmospheric

Table 1
Summary of the principal indices of the DHI assessment procedure

	Name	Description	Range
DHI	Domino Hazard Index	Score of the domino hazard of a unit with respect to the maximum potential to affect possible escalation targets. It can either consider or not consider the effect of passive protection measures.	[0, 100]
DHS	Domino Hazard Score	Score of the domino hazard of a unit with respect to triggering escalation on a specific target unit. It can either consider or not consider the effect of passive protection measures.	[0, 10]
$DHS_{i,k}$	Maximum DHS for escalation from *i*-th to *k*-th unit	Domino Hazard Score considered to assess the worst case of escalation potential between a given pair of units.	[0, 10]
$DHS_{i,k,h}$	Domino Hazard Score for *h*-th scenario from *i*-th to *k*-th unit	Domino Hazard Score with respect to a specific escalation scenario selected among the possible scenarios that can trigger escalation between a given pair of units.	[0, 10]

Table 2
Possible primary events likely to give domino escalation as a function of material hazardous proprieties and operative conditions

	Material classification		
	Flammable	Explosive/reactive	Stable and non-flammable
Physical state			
Liquid	Pool fire, flash fire, VCE	Condensed phase/confined explosion	–
Liquefied gas	Pool fire, jet fire, VCE, flash fire, fireball, BLEVE, physical explosion	Condensed phase/confined explosion, physical explosion, BLEVE	Physical explosion, BLEVE
Gas	Jet fire, flash fire, VCE, physical explosion	Condensed phase/confined explosion, physical explosion	Physical explosion
Solid/dust/mist	Fire, dust explosion, confined explosion	Condensed phase/confined explosion	–

Table 3
Accidental events likely to give rise to domino escalation (classified according to the escalation vector involved) [5]

Escalation vector	Accidental event
Flame impingement/heat radiation	Pool fire, jet fire, flash fire, fireball, VCE
Blast wave	Condensed phase explosion, confined explosion, physical explosion, BLEVE, VCE
Fragment projection	Condensed phase explosion, confined explosion, physical explosion, BLEVE

unit within the fireball area ($D_{i,k} < d_f$) means a score of $DHS_{i,k,h} = 10$; otherwise $DHS_{i,k,h} = 0$.

Fire insulation is a passive measure that is effective in protecting vessels from fireball effects. It should be noted, however, that in general practice fire insulation protects only the lower 10 m of a vessel [1], and fireballs can reach significant heights because of the lift forces involved. Similar considerations apply when protection is provided by fire resistant walls. Nevertheless, if the insulation is complete, some degree of protection is afforded to atmospheric vessels and the appropriate value is $DHS_{i,k,h} = 5$.

2.1.2. Pool fires and jet fires

Escalation scenarios triggered by pool fires or jet fires involve both flame impingement and continuous heat radiation from a distant source. Impinged unprotected vessels are reported to undergo failure in a relatively short time [4,6], and the distances occupied by the flame envelope (d_f) encompass an area where escalation is highly possible ($DHS_{i,k,h} = 10$). The flame dimension (d_f) can be roughly considered equivalent to the pool radius for a non-tilted pool fire. For jet fires, the worst case of horizontal-axis release directed toward the secondary equipment is considered. Thus, the

Table 4
Summary of rules for assignation of Domino Hazard Score (DHS) as a function of the escalation vector

Escalation vector	Secondary unit	Inherent DHS	Protective device	Passive DHS
Flame impingement/radiation				
Flash fire, thermal effect VCE	Free flammable vapors	10	–	
	Other cases	0		
Fireball	Impinged atmospheric vessel	10	Fire insulation	5
	Other cases	0		
Pool fire	Impinged equipment	10	Fire resistance wall	1
			Bund	+1
	Thermal radiation as distant source	Fig. 2	Fire insulation	Fig. 2
Jet fire	Impinged equipment	10	Fire resistance wall/mounding	1
	Thermal radiation as distant source	Fig. 3	Fire insulation	Fig. 3
Blast wave	Unprotected equipment	Fig. 4	Barricade	1
Fragment projection	Unprotected equipment	Fig. 5	Barricade	1

Inherent DHS and passive DHS refer to the possibility of accounting for passive protection devices in DHS evaluation.

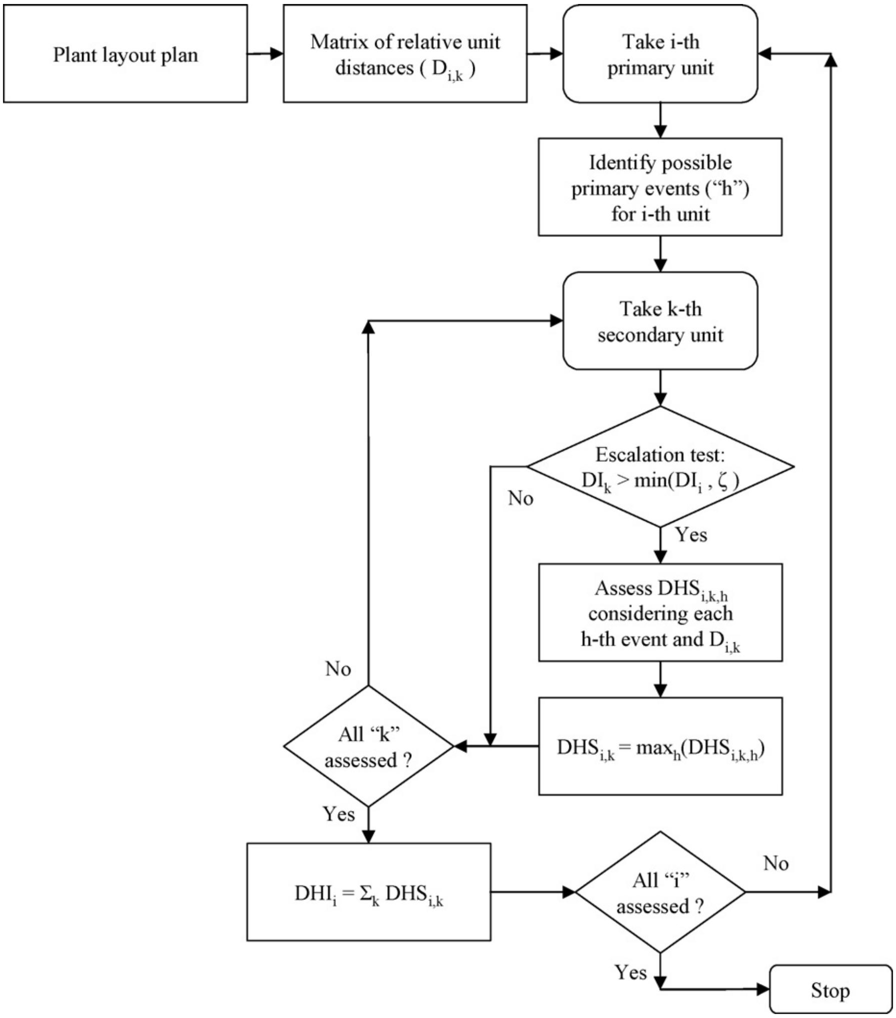

Fig. 1. Conceptual flow diagram of DHI assessment.

distance enveloped by flames (d_f) is the sum of the characteristic dimension of the primary unit on the layout plan (i.e. the distance of the leaking boundary from the geometric centre) and the maximum flame length. Diagrams are available in the literature for a quick estimation of flame length [5].

Concerning the effects of heat radiation, a correlation can be identified between the distance from the flame boundary and the expected time to failure of exposed units [4]. Elaboration of these data results in the DHS values reported in Figs. 2 and 3. The distance from the flame envelope, or radiation-impacted distance (d_r), can be calculated as:

$$d_r = D_{i,k} - d_f - d_s \tag{4}$$

where d_s is the characteristic dimension of the secondary unit on the layout plan (i.e. the distance of the failing unit boundary from the secondary unit geometric centre). $\mathrm{DHS}_{i,k,h}$ can be evaluated by entering d_r from Eq. (4) in the graphs in Figs. 2 and 3, according to the scenario and the secondary unit characteristics.

Fire insulation is a passive measure that is suitable for protecting equipment from these types of escalation events. In the case

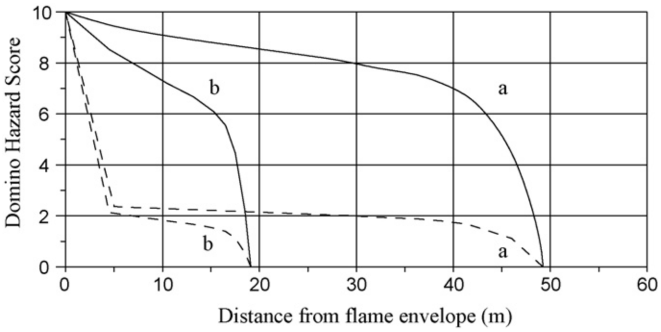

Fig. 2. DHS as a function of the distance from the flame envelope for pool fire scenarios. Solid line: unprotected vessels; dashed line: fire-insulated vessels; atmospheric equipment (a); pressurized equipment (b).

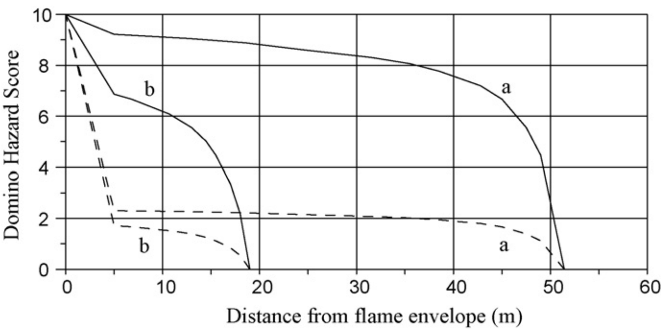

Fig. 3. DHS as a function of the distance from the flame envelope for jet fire scenarios. Solid line: unprotected vessels; dashed line: fire-insulated vessels; atmospheric equipment (a); pressurized equipment (b).

of flame impingement, however, even small defects in insulation continuity nullify the protective behavior [7,8]. Defects can easily originate from damage or ripping, but also from incorrect operations (e.g. removal for inspection and missed replacement). Thus, even for protected targets, no reduction of DHS is accounted for in the case of fire impingement (i.e. $\mathrm{DHS}_{i,k,h} = 10$). On the other hand, in the zone of radiation from a distant source, fire insulation is considered to effectively decrease the risk of escalation by heat load and the values of DHS can be derived from Figs. 2 and 3.

Fire resistant walls provide effective protection from both flame impingement and radiation, and the DHS value is reduced to $\mathrm{DHS}_{i,k,h} = 1$ for equipment in the protected area. The hazard is not completely eliminated because passive devices have an intrinsic probability of failure on demand [9]. Mounded equipment is considered in the present analysis to have a protection value equivalent to fire resistant walls.

For pool fires, a bund limits the area subjected to flame engulfment. However, as with any passive protection measure, bunds are not fully reliable and a one-point increase of DHS (a penalty of +1 to the DHS value in the radiation zone) is assigned if units can be reached by flames in the event of bund failure.

2.2. Blast waves

Blast wave consequences are affected by numerous parameters including the explosion characteristics, blast wave characteristics and reflection phenomena. When far-field interaction between the explosion source and the target equipment is of concern, or when low pressures are considered (static peak overpressure less than 50 kPa), the static peak overpressure can be effectively used to assess the damage caused by the overpressure wave. Hence, it is possible to identify overpressure threshold values for different levels of damage for typical classes of equipment [4,10]. DHS scores have been defined using these thresholds for different magnitudes of loss-of-containment in target vessels, and are reported in Fig. 4. Using a suitable blast wave model (e.g. multi-energy or Baker-Strehlow), the static peak overpressure can be related to the distance (d_b) from the explosion source once the energy released by the explosion is estimated. The distance (d_b) is defined as:

$$d_b = D_{i,k} - d_e - d_s \quad (5)$$

where d_e is the distance of the explosion source from the centre of the primary unit, d_s is the characteristic dimension of the secondary unit (as previously defined), and $D_{i,k}$ is the relative distance between the two units. The distance of the explosion from the primary unit (d_e) can be considered as the geometric position on the layout plan of a failing boundary (e.g. a wall) or a vent in the case of confined explosions, physical explosions and BLEVEs. In the case of VCEs, since weather conditions play a direct role in cloud dispersion, conservative assumptions may be adopted; e.g. considering a hemispheric stoichiometric cloud centered on the unit and assuming the flammable cloud radius to be the explosion source distance (d_e).

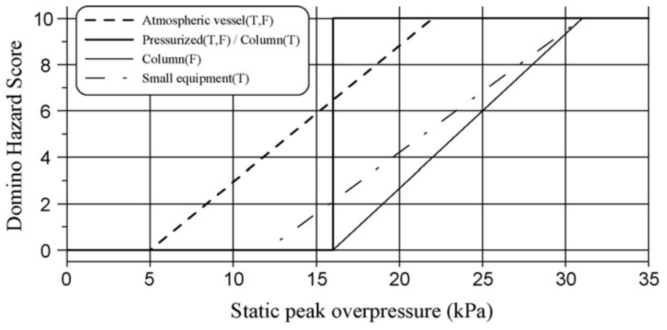

Fig. 4. DHS as a function of the static peak overpressure for blast wave scenarios for different classes of equipment (T: handling toxic material; F: handling flammable material).

Passive measures for limitation of escalation due to overpressure waves mainly consist of barricades such as blast walls or cubicles. These passive devices, within the extent of their feasibility and reliability [9], are considered effective in limiting overpressures in the desired propagation direction (i.e. $\mathrm{DHS}_{i,k,h} = 1$ in the protected zone).

2.3. Fragment projection

The projection of fragments is considered an important cause of domino effects in industrial accidents [1,11–14]. Detailed analysis of the cinematic records of missile projection has enabled the identification of probabilities of hitting targets of a given size as a function of distance [5,13]. From these data, values for DHS as a function of distance and vessel size were derived and are reported in Fig. 5. These cited studies on missile projection, as well as reports from industrial accidents [15,16], show that fragments are capable of generating secondary accidents at large distances from the primary source. Thus, no practical action in layout design (e.g. segregation) can result in a complete negation of escalation possibility. This is recognized in the DHI assessment by a lower limit of unity for the DHS score (see Fig. 5).

The same passive protection measures used for limiting blast wave effects (e.g. blast walls) can also be designed to be effective in blocking missiles. Thus, in the protected area, the appropriate value is $\mathrm{DHS}_{i,k,h} = 1$.

2.4. Toxic release

In the present contribution, only primary events that result in physical effects likely to cause direct escalation were considered. Toxic releases may exert an escalation influence because of indirect effects on emergency procedures and crisis management [11]. Such considerations are, however, beyond the scope of the present analysis.

3. Case study

In this section, a case study is presented to demonstrate the application of the proposed index methodology. The aim of the study is to select an inherently safer layout for an acrylic acid production plant.

3.1. Case study description

The same process was studied earlier from the perspective of inherent safety considerations in process design using the I2SI

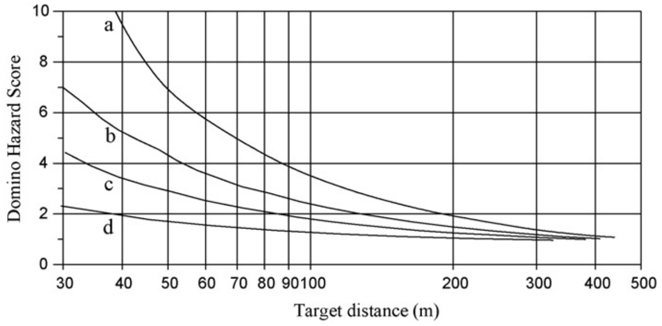

Fig. 5. DHS as a function of the secondary unit distance for fragment projection; curves for different geometrical size of target unit are presented (very large storage vessel (a), large storage vessel (b), medium storage vessel (c), process vessel or small storage vessel (d)).

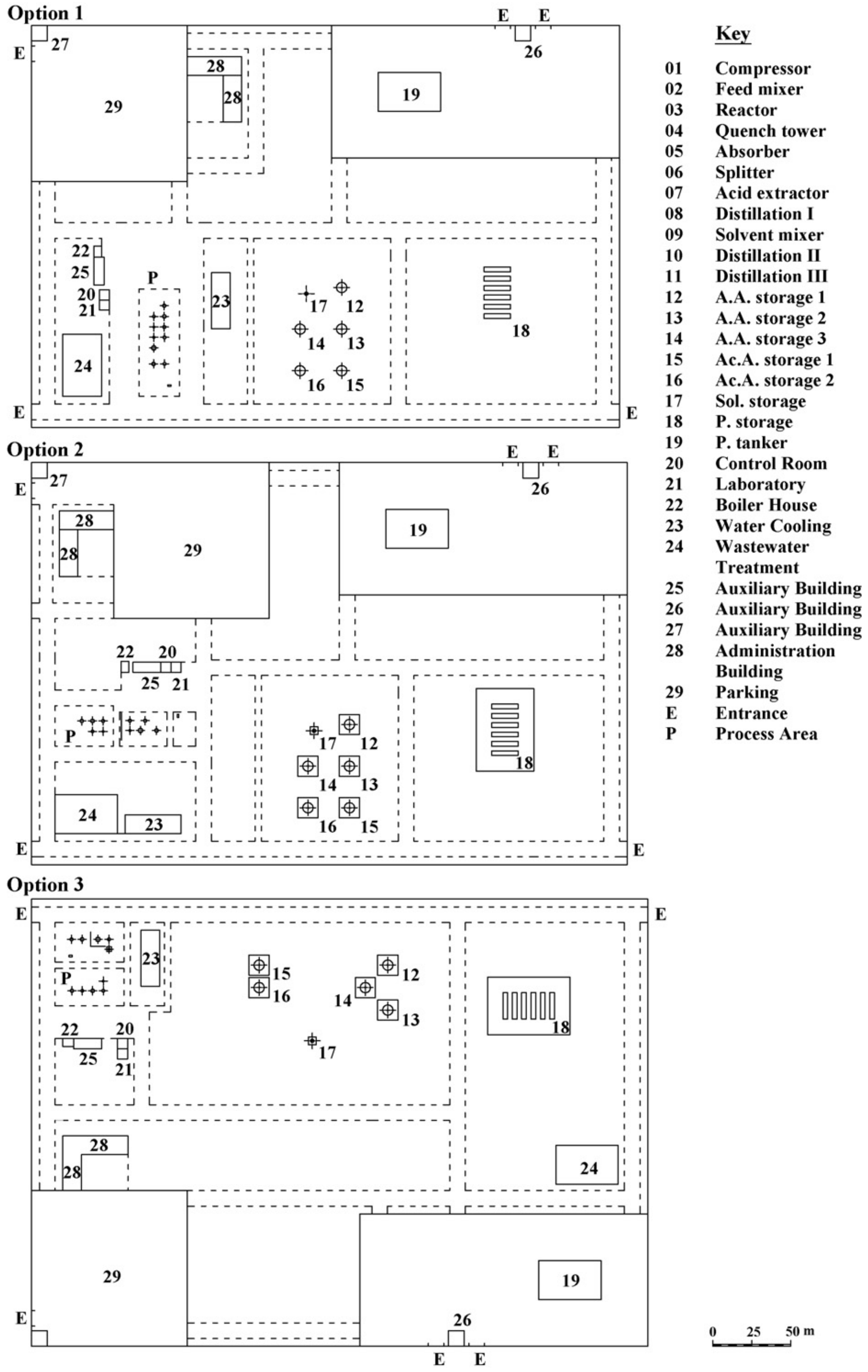

Fig. 6. Layout plan of the three options in the case study.

methodology [17]. This particular acrylic acid process is based on the one-step catalytic oxidation of propylene in the vapor phase. Further process details are described by Palaniappan et al. [18]. In addition to the process units discussed in the previous I2SI application [17], the storage section for feedstock materials and products (propylene, acrylic acid, acetic acid, solvent for make-up), the tank-truck loading facility, and the principal plant utilities have been included in the current layout assessment.

Three possible layout options are proposed and compared here. Figs. 6 and 7 provide details of the general plot layout and the process area layout, respectively. Each option thus presents a different solution for the design of both the overall plot plan and the process area configuration:

- Option 1 (base option) was designed in accordance with typical safety rules used in industrial practice for separation distances ([1,19] and references cited therein). No passive protection devices were considered for this option. The units of the process area are arranged in a single block, in two parallel rows following the process flow order. The storage area can be sub-divided into two main blocks—the pressurized storage of liquefied propylene (comprised of several horizontal vessels) and the atmospheric

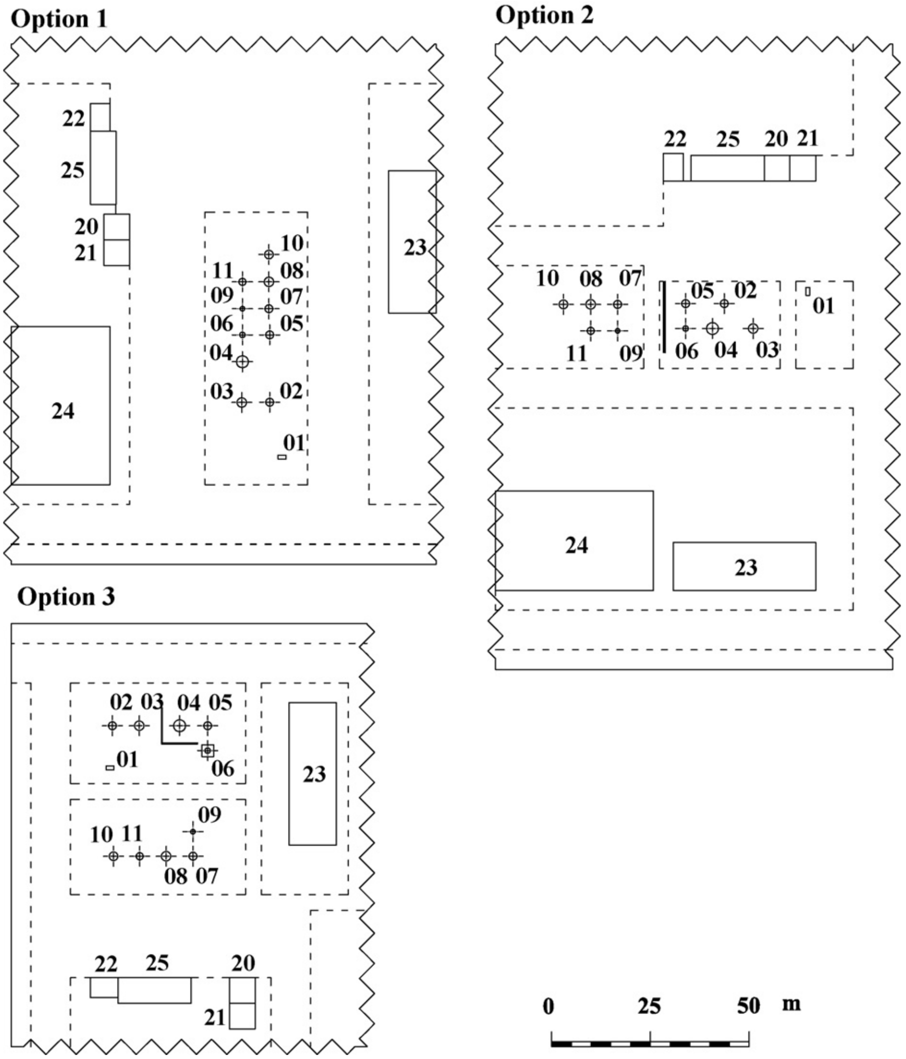

Fig. 7. Layout of the process area of the three options in the case study.

tank farm for storage of the liquids (acrylic acid, acetic acids and solvent).

- Option 2 presents an improved layout in the process area. The units are segregated in two blocks (reaction and product recovery block, and separation block). A wall, acting as both a fire resistant wall and a blast wall, is erected at the edge of the first block. All units have fire insulation in place. The layout of the loading and storage area has the same plot plan as option 1; however, passive protection measures (bunds and fire insulation) are considered in this case.
- Option 3 incorporates segregation of units, a modified spatial arrangement and passive protection devices, all aimed at enhancing layout safety. The units in the process area are arranged in two segregated blocks on a single row. The control room and laboratory are placed at a conveniently safe distance. Fire insulation is in place on all units. In addition, two firewalls to protect the quencher, and a bund to contain possible spills from the splitter, are in place. The layout of the tank farm is improved to limit escalation consequences (maximizing segregation). The distance of the loading facility from the propylene storage area is also increased.

It is worth noting that the assumption of an absence of protective devices in option 1 was made in the current case study to create an extreme case that better demonstrates the application and outcomes of the analysis. In general, there is no requirement for the base case to completely lack passive safety measures. However, the base case is considered a starting option and the other options are designed as possible inherent safety improvements with respect to the base case. Thus, the base case is always expected to have a poor safety performance.

3.2. *Analysis and discussion*

The case study is now analyzed from the perspective of the process area layout and the overall plot plan.

3.2.1. *Process area layout*

The results of the analysis of the three options are presented in Tables 5–12. The process area is discussed first because it consists of closely linked processing units and displays several hazardous features that can trigger escalation events. The process area units considered for all options are listed in Table 5. Data on the relative distances of the units were organized for each layout in the form of a distance matrix; an example for option 3 is given in Table 5. Relevant primary events were identified and the DHI was calculated. An example of the domino hazard scoring is reported in Table 6 for option 3. As explained in the Part 1 (accompanying paper), assessment of the DHI is required for evaluation of the Inherent Safety

Table 5
Example of distances among unit geometric centres in process area of option 3

#	Unit	01	02	03	04	05	06	07	08	09	10	11
01	Compressor	–	10.2	12.6	20.3	26.7	25.0	31.0	26.0	26.2	21.8	23.0
02	Feed mixer	10.2	–	6.8	17.0	24.1	24.9	38.8	35.7	33.7	33.0	33.7
03	Reactor	12.6	6.8	–	10.2	17.3	18.4	35.7	33.7	30.5	33.6	33.0
04	Quencher	20.3	17.0	10.2	–	7.1	9.5	33.2	33.2	27.0	37.0	34.5
05	Absorber	26.7	24.1	17.3	7.1	–	6.3	33.2	34.6	27.1	40.7	37.2
06	Splitter	25.0	24.9	18.4	9.5	6.3	–	27.0	28.7	20.8	35.8	31.8
07	Acid extractor	31.0	38.8	35.7	33.2	33.2	27.0	–	6.8	6.2	20.1	13.5
08	Distillation I	26.0	35.7	33.7	33.2	34.6	28.7	6.8	–	9.2	13.3	6.7
09	Solvent mixer	26.2	33.7	30.5	27.0	27.1	20.8	6.2	9.2	–	21.0	14.9
10	Distillation II	21.8	33.0	33.6	37.0	40.7	35.8	20.1	13.3	21.0	–	6.6
11	Distillation III	23.0	33.7	33.0	34.5	37.2	31.8	13.5	6.7	14.9	6.6	–

Table 6
Example of $DHS_{i,k}$ matrix for process area

#	Secondary unit	Primary unit										
		01	02	03	04	05	06	07	08	09	10	11
01	Compressor	–	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
02	Feed mixer	1	–	10	10	1	1	1	1.1	1	1.4	1.6
03	Reactor	1	10	–	10	1	1	1	1.3	1	1.3	1.7
04	Quencher	1	10	10	–	10	2	1	1	1	0.8	1
05	Absorber	1	10	10	10	–	5	1	1.2	1	1	1.5
06	Splitter	1	n.a.	n.a.	n.a.	n.a.	–	n.a.	n.a.	1.4	1.1	n.a.
07	Acid extractor	1	1.3	1.6	1	0.3	1	–	10	7	10	10
08	Distillation I	1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	–	2.1	10	n.a.
09	Solvent mixer	1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
10	Distillation II	1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.4	–	n.a.
11	Distillation III	1	1.6	1.7	1	1	1	2.5	10	1.8	10	–
	DHI	10	33	33	32	13	12	7	25	18	36	16

Data refer to option 3, considering the effect of passive protection devices. Shaded areas correspond to negligible escalation effects (negative escalation test). Dashed lines group together units belonging to the same block. (n.a.): not assessed, as for condition in Equation (1).

Index, or ISI. This further requires consideration of the extent of applicability of the inherent safety guidewords *attenuation* and *limitation of effects*; thus DHI must be calculated twice for each option (i.e. both with and without passive protection measures). Assessment of the damage distances for each option (again, a requirement for ISI computation) was accomplished in the present case study by means of the SWeHI methodology [20]. Values of the principal indices for the case study analysis are reported in Tables 7–9.

Some general observations can be made concerning the DHS data such as those reported in Table 6. Units located in the same block are placed at close relative distances and domino effects within the block are extremely likely. However, some units have the potential to trigger escalation events at longer distances than others. When this distance is higher than (or at least comparable to) the block characteristic dimensions, placing these units in the same layout block implicitly means accepting a heightened escalation possibility. On the other hand, for units that trigger escalation only at short distances, the location within the block largely determines the possibility of initiating an escalation chain. In block layout design, therefore, the location of these latter units is of strategic importance in limiting the magnitude of accident consequences.

Table 7
Summary of all indices evaluated in the assessment for option 1 (case base)

#	Unit	ISI_a	ISI_s	ISI_l	ISI	HCI	ISPI	DI	PHCI	HI	I2SI
01	Compressor	1.0	1.0	1.4	5.0	11	0.45	7	43	0.17	2.71
02	Feed mixer	1.0	1.0	1.4	5.0	31	0.16	29	56	0.53	0.31
03	Reactor	1.0	1.0	1.4	5.0	42	0.12	47	92	0.52	0.23
04	Quencher	1.0	1.0	1.4	5.0	26	0.19	25	51	0.48	0.40
05	Absorber	1.0	1.0	1.4	5.0	31	0.16	30	57	0.53	0.30
06	Splitter	1.0	1.0	1.4	5.0	21	0.24	21	51	0.41	0.58
07	Acid extractor	1.0	1.0	1.4	5.0	21	0.24	30	47	0.65	0.37
08	Distillation I	1.0	1.0	1.4	5.0	21	0.24	22	45	0.49	0.48
09	Solvent mixer	1.0	1.0	1.4	5.0	21	0.24	20	42	0.47	0.51
10	Distillation II	1.0	1.0	1.4	5.0	21	0.24	21	58	0.36	0.67
11	Distillation III	1.0	1.0	1.4	5.0	21	0.24	27	45	0.59	0.40
12	AA storage 1	1.0	1.0	1.4	5.0	24	0.21	36	56	0.64	0.32
13	AA storage 2	1.0	1.0	1.4	5.0	24	0.21	36	56	0.64	0.32
14	AA storage 3	1.0	1.0	1.4	5.0	24	0.21	36	56	0.64	0.32
15	AcA storage 1	1.0	1.0	1.4	5.0	24	0.21	38	56	0.68	0.31
16	AcA storage 2	1.0	1.0	1.4	5.0	24	0.21	38	56	0.68	0.31
17	Sol storage	1.0	1.0	1.4	5.0	24	0.21	14	55	0.25	0.82
18	P storage	1.0	1.0	1.4	5.0	36	0.14	40	73	0.55	0.25
19	P tanker	1.0	1.0	1.4	5.0	36	0.14	27	73	0.37	0.38

AA: acrylic acid, AcA: acetic acid, Sol: solvent, P: propylene.

Table 8
Summary of all indices evaluated in the assessment for option 2

#	Unit	ISI_a	ISI_s	ISI_l	ISI	HCI	ISPI	DI	PHCI	HI	I2SI
01	Compressor	1.0	1	1.4	5.0	11	0.45	7	43	0.17	2.71
02	Feed mixer	1.0	−10	5.7	5.0	25	0.20	29	56	0.53	0.38
03	Reactor	1.9	1	6.2	6.5	36	0.18	47	92	0.52	0.35
04	Quencher	1.1	1	6.7	6.8	22	0.31	25	51	0.48	0.65
05	Absorber	1.5	−10	7.1	5.0	23	0.22	30	57	0.53	0.41
06	Splitter	3.0	−10	21.5	19.3	17	1.13	21	51	0.41	2.74
07	Acid extractor	5.3	−10	32.6	31.5	17	1.85	30	47	0.65	2.86
08	Distillation I	2.4	1	15.0	15.2	17	0.89	22	45	0.49	1.82
09	Solvent mixer	2.2	1	28.9	29.0	17	1.71	20	42	0.47	3.64
10	Distillation II	3.7	1	9.3	10.0	17	0.59	21	58	0.36	1.66
11	Distillation III	2.0	1	32.3	32.3	17	1.90	27	45	0.59	3.23
12	AA storage 1	1.0	−10	45.1	44.0	24	1.83	36	56	0.64	2.85
13	AA storage 2	1.0	−10	34.1	32.6	24	1.36	36	56	0.64	2.11
14	AA storage 3	1.0	−10	34.5	33.0	24	1.38	36	56	0.64	2.14
15	AcA storage 1	1.0	−10	36.8	35.4	24	1.47	38	56	0.68	2.17
16	AcA storage 2	1.0	−10	41.8	40.6	24	1.69	38	56	0.68	2.49
17	Sol storage	1.0	−10	69.4	68.7	24	2.86	14	55	0.25	11.3
18	P storage	1.0	1	1.4	5.0	36	0.14	40	73	0.55	0.25
19	P tanker	1.0	1	1.4	5.0	36	0.14	27	73	0.37	0.38

AA: acrylic acid, AcA: acetic acid, Sol: solvent, P: propylene.

3.2.1.1. Option 1 (base case). Table 7 depicts the I2SI values for option 1. Since this is the base case, these overall index values are mainly influenced by the HI values. Most of the units in the process area yield results for I2SI that are significantly less than unity. On the other hand, the (air) compressor displays relatively safer performance. This is a consequence of the low damage potential (low DI and hence, low HI) and the modest requirement for hazard control devices in the layout definition (low HCI, yielding an ISPI above the average value). Concerning the other units, distillation II is identified as being somewhat safer than the average—again, because of a lower HI, but this time due to extensive application of control devices (this is the product refining column and monitoring is critical for quality control purposes). As expected, the reactor, because it requires a high level of safety devices, has the poorest inherent safety performance (lowest I2SI).

The results of the cost indexing for option 1 are reported in Table 10. Again, no inherent safety measures are considered to be applied because this is the base case. Hence, the conventional and inherent safety cost indices are identical. It can be observed, however, that the cost indices for all units are below unity, meaning that the cost of safety devices is lower than the expected losses. That is mainly due to the possibility of domino effects which significantly increases the loss parameter values.

3.2.1.2. Option 2. Focusing on option 2 (Table 8), the segregation of the two unit blocks in the process area is effective in reducing the escalation hazard of the units located close to the gap between the blocks. This leads to reduced values of DHI and increased values of ISI for the *attenuation* guideword as compared to the base case (option 1). Safety is further enhanced when passive devices are considered, because the separation wall poses a physical barrier to escalation from one block to the other. The new position of the manned buildings (control room and laboratory) is verified as safer because these buildings are now located further from the units of the product separation block. As a consequence, the value of ISI for the *limitation of effects* guideword is significantly increased. On the other hand, ISI for the *simplification* guideword yields a negative contribution to all the units close to the wall, since the wall represents an obstacle. However, the absolute value of this contribution is judged to be quite small, because in the base option the same units were similarly obstructed by the absence of the gap between

Table 9
Summary of all indices evaluated in the assessment for option 3

#		ISI_a	ISI_s	ISI_l	ISI	HCI	ISPI	DI	PHCI	HI	I2SI
01	Compressor	1.0	1	1.4	5.0	11	0.45	7	43	0.17	2.71
02	Feed mixer	1.7	1	12.0	12.1	21	0.58	29	56	0.53	1.10
03	Reactor	1.7	−10	12.0	6.9	38	0.18	47	92	0.52	0.35
04	Quencher	1.6	−30	12.8	5.0	22	0.23	25	51	0.48	0.47
05	Absorber	8.3	−30	38.3	25.1	27	0.93	30	57	0.53	1.75
06	Splitter	12.2	−30	55.5	48.2	17	2.84	21	51	0.41	6.86
07	Acid extractor	36.4	−30	75.2	78.0	17	4.59	30	47	0.65	7.10
08	Distillation I	3.1	1	16.4	16.7	17	0.98	22	45	0.49	1.99
09	Solvent mixer	5.8	−30	37.8	23.7	17	1.39	20	42	0.47	2.97
10	Distillation II	2.8	−10	13.1	8.9	17	0.53	21	58	0.36	1.48
11	Distillation III	2.7	1	27.0	27.1	17	1.59	27	45	0.59	2.71
12	AA storage 1	1.0	−20	54.6	50.8	24	2.12	36	56	0.64	3.29
13	AA storage 2	1.0	−20	54.6	50.8	24	2.12	36	56	0.64	3.29
14	AA storage 3	1.0	−20	54.6	50.8	24	2.12	36	56	0.64	3.29
15	AcA storage 1	1.0	−20	71.3	68.5	24	2.85	38	56	0.68	4.20
16	AcA storage 2	1.0	−20	71.3	68.5	24	2.85	38	56	0.68	4.20
17	Sol storage	1.9	−30	99.5	94.9	24	3.96	14	55	0.25	15.5
18	P storage	1.1	1	1.5	5.0	36	0.14	40	73	0.55	0.25
19	P tanker	42.9	1	42.7	60.5	36	1.68	27	73	0.37	4.54

AA: acrylic acid, AcA: acetic acid, Sol: solvent, P: propylene.

Table 10
Summary of cost indices evaluated in the assessment for the three options

#	Common to all options (base case)			Option 1		Option 2		Option 3	
	C_{Loss} ($)	$C_{ConvSafety}$ ($)	CSCI	$C_{InhSafety}$ ($)	ISCI	$C_{InhSafety}$ ($)	ISCI	$C_{InhSafety}$ ($)	ISCI
01	32,680	23,500	0.72	23,500	0.72	20,500	0.63	20,500	0.63
02	127,868	44,500	0.35	44,500	0.35	44,423	0.35	37,434	0.29
03	138,266	63,000	0.46	63,000	0.46	54,313	0.39	46,120	0.33
04	126,140	25,500	0.20	25,500	0.20	24,333	0.19	23,985	0.19
05	47,699	32,500	0.68	32,500	0.68	22,588	0.47	25,851	0.54
06	101,186	21,000	0.21	21,000	0.21	17,324	0.17	16,706	0.17
07	69,381	21,500	0.31	21,500	0.31	18,234	0.26	19,738	0.28
08	105,368	20,000	0.19	20,000	0.19	17,652	0.17	17,743	0.17
09	113,504	24,000	0.21	24,000	0.21	17,134	0.15	16,695	0.15
10	114,921	22,000	0.19	22,000	0.19	19,751	0.17	20,259	0.18
11	57,392	18,000	0.31	18,000	0.31	15,554	0.27	15,698	0.27
12	118,432	33,500	0.28	33,500	0.28	30,135	0.25	30,135	0.25
13	118,432	33,500	0.28	33,500	0.28	30,178	0.25	30,135	0.25
14	118,432	33,500	0.28	33,500	0.28	30,176	0.25	30,135	0.25
15	118,432	33,500	0.28	33,500	0.28	30,165	0.25	30,028	0.25
16	118,432	33,500	0.28	33,500	0.28	30,146	0.25	30,028	0.25
17	218,434	33,500	0.15	33,500	0.15	30,081	0.14	32,354	0.15
18	437,977	287,500	0.66	287,500	0.66	275,500	0.63	309,028	0.71
19	389,648	69,500	0.18	69,500	0.18	69,500	0.18	59,664	0.15

For item number, refer to Table 7. C_{Loss}, $C_{ConvSafety}$ and CSCI are the same for all options (being based on the values of the base case).

the blocks. The final result for I2SI is an increase above unity for all units belonging to the product separation block. This reflects the limited possibility of escalation from hazardous units (such as the reactor) in the other block.

From a cost perspective (Table 10), segregation of the process layout into two blocks and the presence of passive measures reduce the requirement for further safety measures—thus lowering overall safety costs. The costs of applied devices and of additional land (i.e. increased space requirements) were considered in the evaluation of the inherent safety cost. The overall effect is one of reducing the unit ISCI value from the base case (option 1). This decrease in ISCI is limited to a maximum factor of about 1.4 (reference unit 05, the absorber, in Table 10), meaning that the safety savings are usually an order of magnitude lower than the total costs. The units exhibiting better performance in this regard are those near the block spacing gap and thus protected by the wall—for example, the aforementioned absorber as well as the solvent mixer (unit 09 in Table 10).

3.2.1.3. *Option 3.*

In the process area of option 3, the unit arrangement increases segregation, effectively reducing the DHI values as compared to the base case. This yields high values of ISI for the *attenuation* guideword (Table 9). However, it also creates limitations on applicability of the *simplification* guideword, since the piping network for connection of the various units is made longer. The increased unit segregation makes the passive devices more effective, since the escalation vectors to be countered are mitigated by distance. This results in high values of ISI for the *limitation of effects* guideword. Some contribution to this index is also provided by the better building location (ISI_{lb}) and the fire resistant wall that limits the possible affected areas (ISI_{la}). Focusing on I2SI, values above unity are obtained for most of the units. In particular, the highest values are obtained for the splitter and acid extractor because the arrangement and the passive protection measures serve to limit escalation possibilities as compared to the base case (option 1). On the other hand, the units with the poorest performance are the reactor and the quencher. This is due to the domino effect from explosions which is not countered by the fire resistant wall.

In option 3 the values of ISCI for all units in the process area are lower than the corresponding CSCI values (Table 10). These cost reductions are limited in extent for the same reasons discussed for option 2. In particular, safety costs are significantly decreased for the reactor (due to unit segregation and the firewall), solvent mixer (due to location), absorber (due to location), and splitter (due to location and bund). It can be observed that the ISCI values are comparable to the results for option 2; thus both options can be considered to be at the same approximate level of cost effectiveness. It should be remembered, however, that option 3 generally displays better performance from an inherent safety perspective.

The analysis of the Loss Saving Index (Table 11) reveals that options 2 and 3 are by far more cost effective in limiting the expected loss from accidental events. This is once again due to the integrated effect of passive and inherent measures. The presence of several negative values means that the cost of these measures is fully compensated for by the expected decrease in loss in the event of an accident. Analyzing the details for each unit generally results in the same outcomes already discussed for the I2SI results. This is due to the predominant effect of the values of DHI on both indices (LSI and I2SI).

3.2.2. *Overall plot plan*

Application of the proposed index methodology to the plot plan of the base case (option 1) reveals that the safety distances from the literature are effective in preventing escalation from storage to process area and vice-versa. This is also due to the choice, derived by safety experience and common to all proposed layouts, of locating the propylene storage at the furthest feasible distance from the process area. This enhances the evaluation of the whole layout, since no significant interactions are then possible between the process and storage areas (except fragment or missile projection—which, as previously discussed, is difficult to limit in practice). Another observation concerning the propylene storage is that this area has the same tank layout in all options and therefore does not require assessment of safety improvement possibilities. (This again highlights the fact that indices such as I2SI are intended to be used in a relative, not absolute, manner to effect risk reduction.) Thus, in the following discussion, only the effect on the other storage units from a single propylene vessel is considered.

As shown in Table 7, the I2SI values for the storage and loading area in option 1 are below unity. The Inherent Safety Index (ISI) has low values, as expected for the base case. The values of Damage Index illustrate that all units have significant damage distances

Table 11
Loss saving indices of the case study

#	Unit	Option 1	Option 2	Option 3
01	Compressor	0.72	0.36	0.33
02	Feed mixer	0.35	0.42	0.49
03	Reactor	0.46	−0.19	−0.27
04	Quench tower	0.20	−0.03	−0.07
05	Absorber	0.68	0.16	−0.06
06	Splitter	0.21	−0.32	−0.65
07	Acid extractor	0.31	−0.24	−0.37
08	Distillation I	0.19	−0.36	−0.41
09	Solvent mixer	0.21	−0.60	−0.65
10	Distillation II	0.19	−0.32	−0.30
11	Distillation III	0.31	−0.30	−0.27
12	AA storage 1	0.28	−0.46	−0.47
13	AA storage 2	0.28	−0.44	−0.47
14	AA storage 3	0.28	−0.44	−0.47
15	AcA storage 1	0.28	−0.45	−0.50
16	AcA storage 2	0.28	−0.46	−0.50
17	Sol storage	0.15	−0.81	−0.82
18	P storage	0.66	0.57	0.52
19	P tanker	0.18	0.18	−0.47

AA: acrylic acid, AcA: acetic acid, Sol: solvent, P: propylene.

and hence significant potential to trigger escalation. As expected, propylene storage appears as a critical safety issue. The storage of solvent, however, is a relatively low hazard unit with respect to escalation.

In option 2 (Table 8), the spatial disposition of the units is the same as in option 1. Thus, the I2SI values principally reflect the effect of passive measures in escalation limitation. The combined protection of bunding and fire insulation increases the index values of the atmospheric storage units for flammable liquids well above unity.

In option 3 (Table 9), the improved unit spatial disposition has no effect in preventing escalation among unprotected atmospheric storage units (low values of ISI_a); however, if combined with passive protection, enhanced safety performance is obtained (high values of ISI_l, mainly due to *limitation of the effects of domino escalation*). On the other hand, the increased segregation does prevent, from an inherent safety perspective, escalation triggered by the propylene tank trucks at the loading station. The I2SI values are well above unity for all units, with good performance of the solvent storage unit made possible by adopting both inherent and passive measures.

Tables 10 and 11 show the results of cost indexing for the storage and loading area. From Table 10, it can be observed that storage units usually have large costs of losses, mainly due to the large extent of damage propagation by domino effect. For storage, ISCI values are therefore lower than unity, suggesting that further protective measures should be applied. Option 2 shows only a minor decrease in ISCI values compared to those for CSCI for the storage area. This is a direct consequence of the similar values of costs for conventional safety and inherent safety. The same conclusions generally hold for option 3. Here, though, the inherent safety cost for propylene storage is higher than the conventional safety cost because of the high land cost for unit separation.

Analysis of the Loss Saving Index results in Table 11 leads to the same conclusions as those drawn for the process area. The loading facility offers a clear example of the previously discussed effect of DHI performance on both LSI and I2SI.

Table 12
System I2SI values for process area, storage area and the whole plant

	Process units	Storage and loading units	Whole plant
Option 1 (base case)	1.8×10^{-2}	1.6×10^{-2}	2.9×10^{-4}
Option 2	5.2×10^{0}	8.6×10^{0}	4.5×10^{1}
Option 3	3.2×10^{1}	1.1×10^{2}	3.4×10^{3}

Table 12 reports the system I2SI for each of the three options. The better performance of the whole plant clearly belongs to option 3 due to the positive contribution of every unit. The contribution to the system index of the two identified plant areas (process area and storage area) is equally balanced in options 1 and 2, while a difference of one order of magnitude is shown by option 3. This is mainly due to the good performance achieved by coupling segregation and passive protection in facility layout.

4. Conclusion

An index approach for the evaluation of domino hazards in the early stages of process design has been developed. The index is based on the assessment of scenarios able to trigger domino escalation. A quick scoring system was developed to quantify the domino hazard related to each single unit. The scoring is able to account for the effects of inherent and passive measures which are implemented in the design. In the general framework of the methodology described in this two-part contribution, the Domino Hazard Index provides a reference for the analysis of layout performance in the early stages with respect to safety and implementation of inherent safety principles (thus reducing the subjectivity usually associated with an analysis of these aspects).

Application of the proposed safety index methodology to a case study has demonstrated the effectiveness of the approach. The methodology permits identification of the critical units within a given layout, and assessment of the inherent safety performance of alternative options. General conclusions drawn from the case study include:

- The use of segregation is indeed effective in preventing domino chains, thus improving the inherent safety of the layout. Considering the whole plant, however, an integrated application of inherent and passive measures appears as the desirable way to achieve the best layout safety performance.
- Grouping the units in blocks generally implies accepting the domino effects within a given block. The position of minor units should be carefully designed to limit initiation possibilities for chain effects.
- The economic consequences of loss for domino effects are typically significant. Therefore, limiting domino possibility by improved layout design yields important savings in terms of the avoided costs of accidents.

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References

[1] F.P. Lees, Loss Prevention in the Process Industries, second ed., Butterworth-Heinemann, Oxford, UK, 1996.
[2] C. Delvosalle, C. Fievez, A. Pipart, B. Debray, ARAMIS project: a comprehensive methodology for the identification of reference accident scenarios in process industries, J. Hazard. Mater. A130 (2006) 200–219.
[3] F.I. Khan, P.R. Amyotte, Integrated inherent safety index (I2SI): a tool for inherent safety evaluation, Proc. Safety Prog. 23 (2004) 136–148.
[4] V. Cozzani, G. Gubinelli, E. Salzano, Escalation thresholds in the assessment of domino accidental events, J. Hazard. Mater. A129 (2006) 1–21.
[5] V. Cozzani, A. Tugnoli, E. Salzano, Prevention of domino effect: from active and passive strategies to inherently safer design, J. Hazard. Mater. A139 (2007) 209–219.
[6] V. Cozzani, G. Gubinelli, E. Salzano, Criteria for the escalation of fires and explosions, in: Proc. Seventh Proc. Plant Safety Symp., AIChE, vol. 225, New York, NY, USA, 2005.
[7] J.D.J. VanderSteen, A.M. Birk, Fire tests on defective tank-car thermal protection systems, J. Loss Prev. Proc. Ind. 16 (2003) 417–425.
[8] A.M. Birk, D. Poirier, C. Davison, On the thermal rupture of 1.9 m3 propane pressure vessels with defects in their thermal protection system, J. Loss Prev. Proc. Ind. 19 (2006) 582–597.
[9] AIChE, Layer of Protection Analysis: Simplified Process Risk Assessment, American Institute of Chemical Engineers (Center for Chemical Process Safety), New York, NY, USA, 2001.
[10] E. Salzano, V. Cozzani, A fuzzy set analysis to estimate loss intensity following blast wave interaction with process equipment, J. Loss Prev. Proc. Ind. 19 (2006) 343–352.
[11] F.I. Khan, S.A. Abbasi, Models for domino effect analysis in chemical process industries, Proc. Safety Prog. 17 (1998) 107–123.
[12] CCPS, Guidelines for Chemical Process Quantitative Risk Analysis, second ed., American Institute of Chemical Engineers (Center for Chemical Process Safety), New York, NY, USA, 2000.
[13] G. Gubinelli, S. Zanelli, V. Cozzani, A simplified model for the assessment of the impact probability of fragments, J. Hazard. Mater. A116 (2004) 175–187.
[14] R. Pula, F.I. Khan, B. Veitch, P.R. Amyotte, A model for estimating the probability of missile impact: missiles originating from bursting horizontal cylindrical vessels, Proc. Safety Prog. 26 (2007) 129–139.
[15] W.E. Westin, Summary of Ruptured Tank Cars Involved in Past Accidents, Report No. RA-01-2-7, Railroad Tank Car Safety Research and Test Project, Chicago, IL, USA, 1971.
[16] P.L. Holden, A.B. Reeves, Fragment hazards from failures of pressurised liquefied gas vessels, IChemE Symposium Series No. 93, 1985.
[17] F.I. Khan, P.R. Amyotte, I2SI: a comprehensive quantitative tool for inherent safety and cost evaluation, J. Loss Prev. Proc. Ind. 18 (2005) 310–326.
[18] C. Palaniappan, R. Srinivasan, R. Tan, Expert system for the design of inherently safer processes. 2. Flowsheet development stage, Ind. Eng. Chem. Res. 41 (2002) 6711–6722.
[19] J.C. Mecklenburg, Plant Layout, John Wiley & Sons, New York, NY, USA, 1973.
[20] F.I. Khan, T. Husain, S.A. Abbasi, Safety weighted hazard index (SWeHI): a new, user-friendly tool for swift yet comprehensive hazard identification and safety evaluation in chemical process industries, Proc. Safety Env. Protect 79 (2001) 65–80.