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Safety assessment in plant layout design using indexing approach: Implementing inherent safety perspective
Part 1 – Guideword applicability and method description

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ABSTRACT

Layout planning plays a key role in the inherent safety performance of process plants since this design feature controls the possibility of accidental chain-events and the magnitude of possible consequences. A lack of suitable methods to promote the effective implementation of inherent safety in layout design calls for the development of new techniques and methods. In the present paper, a safety assessment approach suitable for layout design in the critical early phase is proposed. The concept of inherent safety is implemented within this safety assessment; the approach is based on an integrated assessment of inherent safety guideword applicability within the constraints typically present in layout design. Application of these guidewords is evaluated along with unit hazards and control devices to quantitatively map the safety performance of different layout options. Moreover, the economic aspects related to safety and inherent safety are evaluated by the method. Specific sub-indices are developed within the integrated safety assessment system to analyze and quantify the hazard related to domino effects. The proposed approach is quick in application, auditable and shares a common framework applicable in other phases of the design lifecycle (e.g. process design). The present work is divided in two parts: Part 1 (current paper) presents the application of inherent safety guidelines in layout design and the index method for safety assessment; Part 2 (accompanying paper) describes the domino hazard sub-index and demonstrates the proposed approach with a case study, thus evidencing the introduction of inherent safety features in layout design.

1. Introduction

Plant layout plays an important role in defining the safety of a facility. The spatial arrangement of process units influences the ability of an accidental event to propagate from one unit to another (domino effect), resulting in escalation of the magnitude of the accident consequences [1,2]. As well, the position of populated targets (e.g. buildings) with respect to possible sources of hazard is of major concern due to the possibility of exposure and fatalities. Moreover, layout design affects the accessibility of the different areas in a plant, which is a critical element for both accident risk (e.g. easy, regular operations and maintenance) and accident management (e.g. fire-fighting operations and evacuation).

Plant layout design involves several different issues that have to be considered at the same time: constraints on process requirements, cost, safety, services and utilities availability, plant construction, regulations, etc. Layout design is usually performed in successive steps of increasing detail. Design strategies and computer aided-tools have been developed to assist in the various steps (see, for example, [3,4] and the references cited therein). Current research worldwide on design analysis tools is focused primarily on optimization of the economic aspects of the facility plot (see, for example, [5–8]). From the safety point of view, early layout design is mainly based on industrial practice and simple guidelines or empirical rules. Tables of conventional segregation distances for various equipment units are traditionally used in this regard [3,4]. Some attempts to include safety aspects in layout optimization have been made [9–11]; these are aimed mainly at economic optimization of layout design, including the assessment of safety aspects (e.g. cost of safety devices and of losses). A more detailed safety analysis, involving evaluation of possible accidental scenarios and consequence analysis, is generally confined to the final stages of the design lifecycle when the risk performance of the whole plant is verified. There are, however, limited margins for layout improvement left at this stage. Hence, there exists a need for an engineering

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Nomenclature

$a_{i,j}$	hazard index for *j*th building or sensible target to be hit by *i*th unit
AA	area affected by the potential accident consequence (m^2)
A_j	hazard index for *j*th building or sensible target
B_i	maximum damage distance of *i*th unit (m)
C_a	cost of attenuation ($)
$C_{Add\text{-}on}$	cost of add-on safety measures ($)
C_{AL}	value of direct asset loss ($)
$C_{Control}$	cost of process control measures ($)
$C_{ConvSafety}$	cost of conventional safety ($)
C_{DEC}	value of domino escalation cost ($)
C_{ECC}	environmental cleanup cost ($)
C_{HHL}	value of human health loss ($)
$C_{InhSafety}$	overall cost of safety with inherent safety implementation ($)
$C_{Inherent}$	cost of inherent safety implementation ($)
C_l	cost of limitation of effects ($)
C_{Loss}	value of expected loss ($)
C_{PL}	value of production loss ($)
CSCI	Conventional Safety Cost Index
C_{si}	cost of simplification ($)
DHI	Domino Hazard Index
DHS	Domino Hazard Score
DI	Damage Index
E_a	extent of applicability of the guideword attenuation
E_l	extent of applicability of the guideword limitation of effects
E_{la}	extent of applicability of the guideword limitation of the affected area
E_{lb}	extent of applicability of the guideword limitation of the damage potential to target buildings
E_{le}	extent of applicability of the guideword limitation of the effects of domino escalation
E_{si}	extent of applicability of the guideword simplification
HCI	Hazard Control Index
HI	Hazard Index
I2SI	Integrated Inherent Safety Index
ISCI	Inherent Safety Cost Index
ISI	Inherent Safety Index
ISI_a	Inherent Safety Index for guideword attenuation
ISI_l	Inherent Safety Index for guideword limitation of effects
ISI_{la}	Inherent Safety Index for guideword limitation of the affected area
ISI_{lb}	Inherent Safety Index for guideword limitation of the damage potential to target buildings
ISI_{le}	Inherent Safety Index for guideword limitation of the effects of domino escalation
ISI_{si}	Inherent Safety Index for guideword simplification
ISPI	Inherent Safety Potential Index
LSI	Loss Saving Index
n	number of items
PHCI	Process and Hazard Control Index
s_k	credit factor for domino escalation toward the *k*th secondary target
SWeHI	Safety Weighted Hazard Index

Greek letter

η	minimum value of ISI

tool that is applicable in the early stages of each step of the process design lifecycle.

Inherent safety can be effectively implemented in the layout structure beginning with the early stages of layout design. Inherent safety aims for the elimination, or the ‘reasonably practicable’ reduction, of the hazards in a system [12]. The key idea of the inherent safety approach is the intuitive concept that a truly inherently safe system cannot possibly fail. This nullifies the requirement for safety devices to reduce the risk of accidents (likelihood and/or consequences) to acceptable levels. Although hazards cannot be completely eliminated in the process industries, a wide range of opportunities and improvements which lead to inherently safer systems are possible. Thus, inherent safety is usually considered in relative terms. Moreover, inherently safer systems can reduce the high costs usually associated with the full plant lifecycle – from hazard management to regulatory liabilities and safety system maintenance [13–16]. Over the past few decades, the scientific literature has discussed the theory of inherent safety [17–22] and has proposed various assessment tools for inherent safety application [23–37,16]. The attention in this previous work was manly focused on the phases of chemical route selection and conceptual process design. Despite these concerted efforts, no comprehensive inherent safety assessment tool specifically addressing the assessment of early layout design is currently available. A first work in this field by Cozzani et al. [2] explored the potential for pursuing inherent safety from the perspective of domino effects in the early layout design stages. This work identified simple quantitative criteria for the design of inherently safer plot plans.

The goal of the present work is to bring inherent safety concepts into the early stages of layout design by means of an easy-to-use approach. This requires consideration of the role of both strictly inherent as well as passive safety measures in achieving layout safety. An index-based assessment tool specifically aimed at the comparison of preliminary alternative layout options is presented. The evaluation is based on an integrated analysis of the different aspects concerning process unit hazards, inherent safety guideword applicability, safety device requirements, and safety economics. The level of information detail required by the assessment procedure is compatible with the data that are typically available in the early design phases. The framework of the Integrated Inherent Safety Index (I2SI) developed by Khan and Amyotte [16,37] was chosen for the newly proposed layout assessment tool. This is in keeping with an overall objective of providing a portfolio of tools with a common structure for the assessment of inherent safety aspects in both process design (previous applications of I2SI as described in [16,37]) and layout design (present contribution). The sub-indices of the original I2SI have been revised in the current work to match the unique issues of layout safety assessment. Specific criteria for safety performance scoring with respect to domino escalation are proposed; the safety cost indexing procedure developed accounts for the potential extent of domino effects in determining accidental losses.

The presentation of this work is divided in two parts. The current paper (Part 1) presents the index method for safety assessment and illustrates the application of inherent safety guidelines in layout design. An accompanying paper (Part 2) describes the above-mentioned domino hazard sub-index and demonstrates the proposed approach with a case study of layout design.

2. Inherent safety in layout design and proposed assessment method

The basic principles of inherent safety are given by an extensive list of guidewords [14]; in common practice, these principles can be effectively addressed by a more restricted group of key guidewords

[38]. Although the terminology of inherent safety varies somewhat throughout the process safety community, there exists a general commonality of thought on the meaning of the different principles when expressed with alternate labels. In the present work, the key guidewords employed are: *minimization*, *substitution*, *attenuation*, *simplification*, and *limitation of effects*. In the current authors' previous work, the principle of *moderation* has generally been used to capture both *attenuation* and *limitation of effects* (although not always, as evidenced by the evaluation study performed by Khan et al. [35]). Layout design is, however, an area where the use of the latter two guidewords in place of the former one is deemed beneficial.

The identified guidewords represent a roadmap of basic rules to improve the inherent safety of a system. They can be applied both at different stages of the system design cycle and at different levels of the safety strategies for control. In the present work, the design stage of concern is layout design, with particular reference to the early phases (design of process items and utilities location, building locations, on-site roads and accessways, etc.). The safety strategies for control can be conventionally and hierarchically classified as *inherent*, *passive* (*engineered*), *active* (*engineered*), and *procedural*. Application of the inherent safety guidewords to the inherent safety strategies themselves is obviously the most effective and straightforward approach, and has received the majority of attention in prior development of assessment tools [22]. However, the guidewords can also be applied at the other levels of the hierarchy, for example leading to add-on measures that are more reliable, effective and thus – in a broad sense – inherently safer. In the current work, both strictly inherent measures as well as passive measures have been investigated for their ability to improve the safety performance of the layout plot. The perspective of layout design considered here, therefore, is one in which the entire set of items placed in the facility (no matter if they are pieces of equipment or blast walls) contributes in defining the global hazard of the plant as a system (e.g. the potential for maximum domino effect escalation). This shift in perspective justifies the choice to consider both safety strategy levels (inherent and passive) in the current analysis. Active and procedural safety strategies are not considered here because, by their definition, they do not generally belong to the first stages of layout design.

An index approach was selected to quantify the effects of the inherent and passive choices on the safety of layout plot plans. In particular, the index aims to evaluate different layout options by identifying the safer alternatives and highlighting critical areas of concern. An indexing method was adopted because such an approach is particularly suitable for the early stages of design when a limited amount of information is available. In the development of the proposed tool, the assessment framework of the previously formulated Integrated Inherent Safety Index, or I2SI [16,37], was adopted because of the following features:

- I2SI is an indexing approach structured to assess in a comprehensive manner various aspects of inherent safety, with particular reference to guideword applicability.
- It can be easily adapted to the specific design issues of different phases of the design lifecycle, such as layout design in this case, while maintaining the same general structure.
- The application is simple and quick, requiring details that are ready available or estimable.
- I2SI employs inherent safety guidewords in a manner similar to the well-accepted and practiced HAZOP methodology.
- Quantitative scores are provided to help with the interpretation of results and design decision-making.
- I2SI requires a limited amount of expertise to be used.

The use of I2SI in layout design and evaluation first required review and revision of the sub-indices of the original assessment procedure. Constraints related to previous design steps (e.g. chemical route choice, process design, equipment selection, etc.) exist in layout design. These constraints limit the applicability of measures aimed at enhancing inherent safety in the layout options. The previously described inherent safety principles are reviewed below with respect to their applicability in layout design:

- The *minimization* guideword is generally not applicable because equipment characteristics and material inventories have already been selected in previous design phases. If options of changing inventories are still open, they are likely to principally affect storage sections. In the design of equipment layout, the application of this guideword is fairly impractical.
- The *substitution* guideword in layout design, both for equipment and materials, is affected by limitations similar to *minimization*. Thus, *substitution* applicability is generally limited.
- The *attenuation* guideword, in its usual reference to changes in unit operating conditions, has limited applicability as these conditions will have been fixed in previous design steps. However, this guideword may be applied to changes in the arrangement of units. Changing unit arrangement and/or increasing unit segregation reduces, if not eliminates, the potential of domino effects and thus the hazard within the system. This is a key point because accident escalation by domino effect has been identified as the most important hazard source related to process layout design [2]. The effectiveness of layout in reducing this hazard is thus the application of the guideword *attenuation* for the plant considered as a system (i.e. from the perspective of layout analysis). Further justification for this viewpoint can be found in the work of Kletz [14]. His original definition of *attenuation* in process design (processing hazardous materials under less hazardous conditions – e.g. low pressure and temperature) can be revised in the case of layout design as 'using hazardous units in the least hazardous form' (i.e. the layout which limits the domino potential). In essence, the current work is proposing that just as the materials being processed are the building blocks of process design, so then the process units are the building blocks of layout design.
- The *simplification* guideword is readily applicable to layout design. The choice of unit spatial organization has great potential to affect the simplicity of a plant. Complexity can easily arise as the disposition of units diverts from the logical process flow order, or as further items (e.g. walls, equipment of other production lines, and buildings) are added to the plan. Therefore, it is quite likely that layout design choices, even if oriented to satisfy the other inherent safety guidewords, eventually result in a negative feedback with respect to *simplification*.
- *Limitation of effects* is a guideword that deals with the reduction of the extent of negative consequences arising from accidental events. Accepting that a negative effect may somehow occur, this guideword implies a consideration of the measures aimed to limit consequences. In early layout design both inherent and passive strategies can be implemented to pursue this goal. Thus, the *limitation of effects* guideword has been considered in the safety analysis of both inherent and passive measures. Three main applications of *limitation of*. . . in layout design were identified:
    - (i) *Limitation of the effects of domino escalation*: reduction of the effects and consequences of domino escalation events, considering the integrated action of inherent and passive strategies. Note that this is a different aspect than the one considered for the applicability of the *attenuation* guideword. With *attenuation*, the focus was on reduction of the embedded hazard, such reduction being attained only by inherent

Table 1
Modifications of the former I2SI methodology introduced in the current work for analysis of layout safety

- *Inherent Safety Index* (*ISI*) is reviewed to consider the specific issues of layout design.
- A new *ISI for attenuation* is defined to account for domino hazards.
- *ISI for simplification* is extended to account for increase of complexity.
- Three new sub-indices are defined for *ISI for limitation of effects*.
- Reference indices are provided to reduce subjectivity in the evaluation of the extent of applicability of inherent safety guidewords.
- The index *PHCI* in *ISPI* is limited to the hazard control measures (*HCI*).
- Explicit accounting of *costs of domino effect escalation* is implemented in cost indices.
- *LSI* is introduced for a better evaluation of costs of losses.

measures. With *limitation of effects*, the focus is on the effects themselves that can be controlled by both inherent and passive strategies.

(ii) *Limitation of the damage potential to target buildings:* appropriate location of buildings (workshops, administrative buildings, trailers, etc.) and control or emergency structures (control room, medical centre, etc.) in the layout plan so as to limit harm to people and impairment of accident response.

(iii) *Limitation of the affected area:* limitation (generally by passive measures) of the spatial area affected by the consequences of an accidental event, regardless of the effects on other units, buildings, etc.

The conclusion from the above examination is that out of the five guidewords, three (*attenuation*, *simplification* and *limitation of effects*) are of particular interest for the safety assessment of layout plans.

As mentioned earlier, the potential for domino effects is a core issue in layout analysis. To guide the assessment of this aspect within the present methodology, an index – Domino Hazard Index (DHI) – was developed. The DHI quantifies the extent of possibility of domino escalation from single units of the plant. The procedure for DHI assessment derives from an analysis of previous extensive

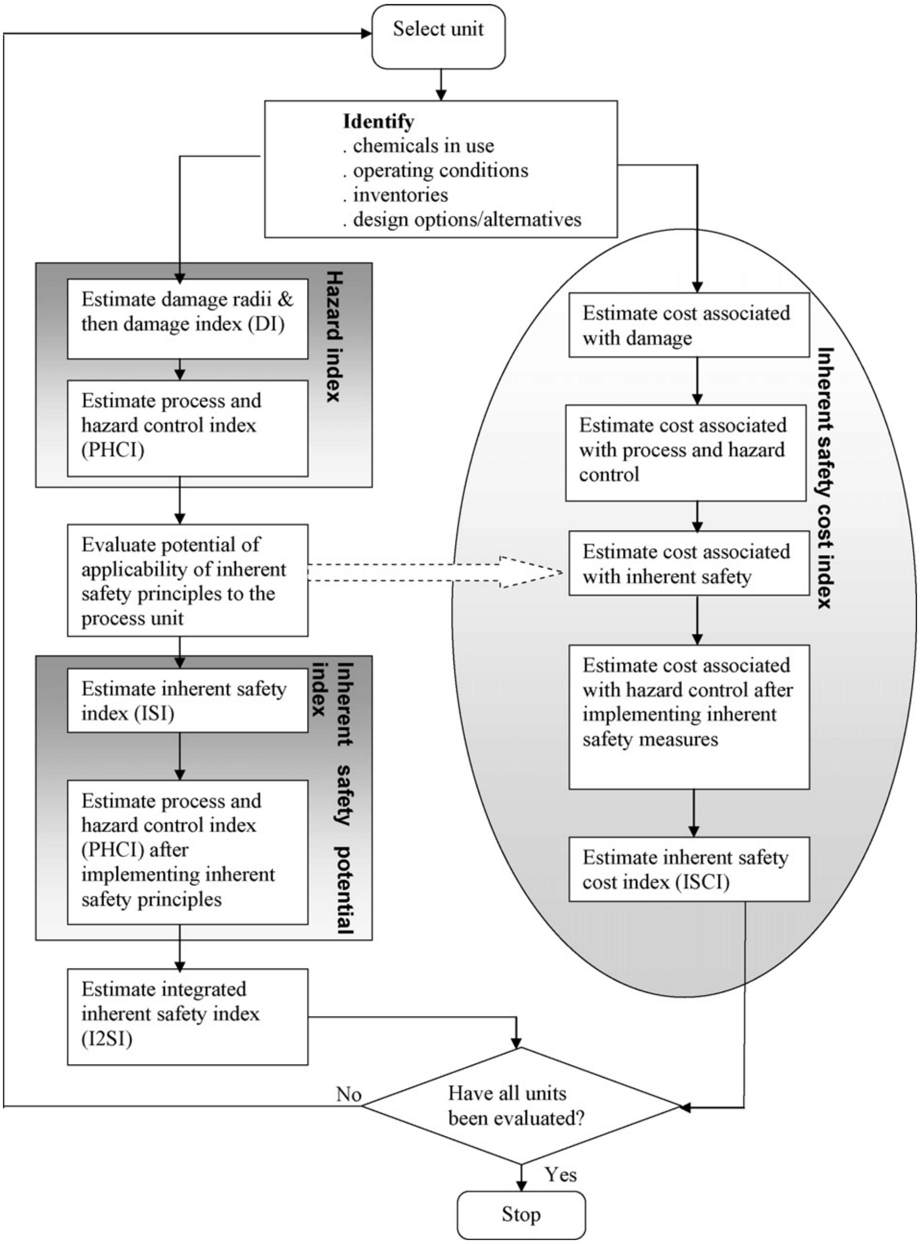

Fig. 1. Conceptual flow diagram of the I2SI assessment method.

work by the current authors on the domino escalation dynamics in process plants [39–43]. The DHI assessment is presented in Part 2 (accompanying paper) of the present work.

A brief illustration of I2SI and a more detailed description of the specific features developed for layout assessment are now presented. Table 1 provides a summary of the main modifications introduced to the original I2SI. For a detailed description of the I2SI framework, the original references [16,37] may be consulted. A case study application of the proposed approach is presented in Part 2 (accompanying paper) of the present work.

2.1. The Integrated Inherent Safety Index in layout analysis

The conceptual framework of the Integrated Inherent Safety Index is given in Fig. 1. The assessment of a layout option is achieved through calculation of a comprehensive system of indices addressing specific aspects of concern for inherent safety. Table 2 summarizes the indices used in the method and gives their definition and range of values. Despite the number of indices, the assessment is relatively quick and straightforward; however, the use of a software tool (e.g. spreadsheet) may provide useful support for swift calculation. The information items necessary to perform the assessment of a layout option are a preliminary definition of the plant plot and of the parameters necessary to describe the hazards of the pieces of equipment (chemicals and their proprieties, operative conditions, reactions, material balances, evaluation of the inventories, and definition of the control systems). The latter information is typically well-known in the case of layout assessment since the basic design of the units is defined in earlier stages (as previously discussed).

The first step of I2SI assessment for safety in layout is the identification of the units in a given option. For each unit, the I2SI is comprised of two main sub-indices: a Hazard Index (HI) and an Inherent Safety Potential Index (ISPI). The Hazard Index is a measure of the damage potential of a single unit after taking into account the process and hazard control measures. The Inherent Safety Potential Index, on the other hand, accounts for the applicability of the inherent safety principles (or guidewords) to the unit. The HI is calculated for the units of an arbitrary reference layout option – called the base case – and the values remain the same for the corresponding units in all other possible options. The HI and ISPI are combined to yield a value of the Integrated Inherent Safety Index as shown in Eq. (1):

$$\mathrm{I2SI} = \frac{\mathrm{ISPI}}{\mathrm{HI}} \tag{1}$$

As evident, an I2SI value greater than unity denotes a positive response of the inherent safety guideword application (i.e. an inherently safer option). The higher the value of I2SI, the more pronounced the inherent safety impact.

To evaluate alternative layout options for the same plant, the I2SI values for all the *N* considered single units are combined according to Eq. (2):

$$\mathrm{I2SI}_{\mathrm{system}} = \left(\prod_{i=1}^{N} \mathrm{I2SI}_i \right)^{1/2} \tag{2}$$

The Hazard Index for layout assessment is evaluated for each unit following the same procedure as for process assessment [37]. The HI is comprised of two sub-indices: a Damage Index (DI) and a Process and Hazard Control Index (PHCI). The numerical value of HI for the unit being considered is calculated by dividing the DI by the PHCI, as shown in Eq. (3):

$$\mathrm{HI} = \frac{\mathrm{DI}}{\mathrm{PHCI}} \tag{3}$$

The Damage Index is a function of four hazard parameters, namely: fire and explosion, acute toxicity, chronic toxicity, and environmental damage. These are estimated as a function of the expected damage radii for each scenario and have values ranging up to 100. Damage radii may be calculated using simple, validated approaches such as the Safety Weighted Hazard Index, or SWeHI,

Table 2
Summary of the principal indices and sub-indices of the assessment methodology

	Name	Description	Range
I2SI	Integrated Inherent Safety Index	Ratio of ISPI and HI (Eq. (1)): balance between the actual application of inherent safety and the actual hazard of the unit.	[0.005; 200]
ISPI	Inherent Safety Potential Index	Ratio of ISI and HCI (Eq. (4)): balance between the hazard reduction by inherent safety guidewords and the residual requirement of add-on controls.	[0.1; 20]
ISI	Inherent Safety Index	Score based on the extent of applicability and on the ability to reduce the hazard, assessed with respect to each inherent safety guideword (Eq. (5)).	[5; 100]
HCI	Hazard Control Index	Sum of the relevant PHCI_x: requirement of add-on hazard control measures in order to achieve an acceptable level of safety for the unit.	[5; 50]
HI	Hazard Index	Ratio of DI and PHCI (Eq. (3)): balance between the hazard of the unit and the requirement of add-on process and hazard control measures.	[0.1; 20]
DI	Damage Index	Sum of the relevant DI_x: hazard score of the unit with respect to the potential to adversely affect the surrounding area.	[10; 200]
PHCI	Process and Hazard Control Index	Requirement of add-on process and hazard control measures in order to achieve an acceptable level of operability and safety for the unit.	[10; 100]
ISI_x	ISI for guideword *x*	Score based on the extent of applicability and the ability to reduce the hazard with respect to the *x*th inherent safety guideword.	[0; 100]
DI_x	DI for damage vector *x*	Score of the ability to affect the surrounding area by the *x*th specific damage vector (fire, explosion, toxic release and environmental contamination).	[0; 100]
PHCI_x	PHCI for add-on control *x*	Requirement of the *x*th type of add-on process or hazard control measure in order to achieve an acceptable level of operability and safety.	[0; 10]
E_x	Extent of applicability of guideword *x*	Evaluation of the extent of applicability and the ability to reduce the hazard with respect to the *x*th inherent safety guideword.	[0; 10]
CSCI	Conventional Safety Cost Index	As for Eq. (13), cost balance between achieving an acceptably safe unit (cost of conventional safety measures) and the expected economic consequence of an accident (cost of losses).	[0; +∞]
ISCI	Inherent Safety Cost Index	As for Eq. (16), cost balance between cost of safety for an inherently safer unit (marginal cost of inherent safety + cost of additional measures) and the expected cost of losses in case of accident.	[0; +∞]
LSI	Loss Saving Index	As for Eq. (18), cost balance between the net savings from reduction of the expected domino losses by inherent safety implementation and the expected cost of losses in case of domino accident.	[−∞; +∞]

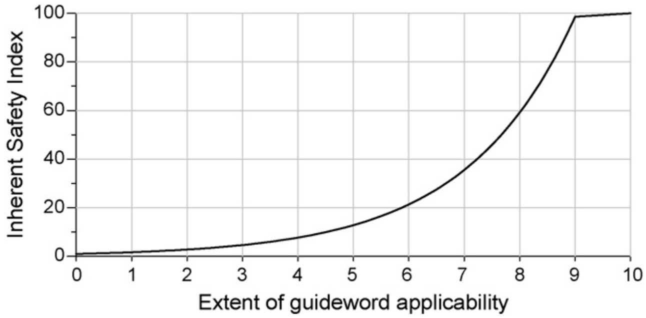

Fig. 2. Inherent Safety Index for the *attenuation* guideword.

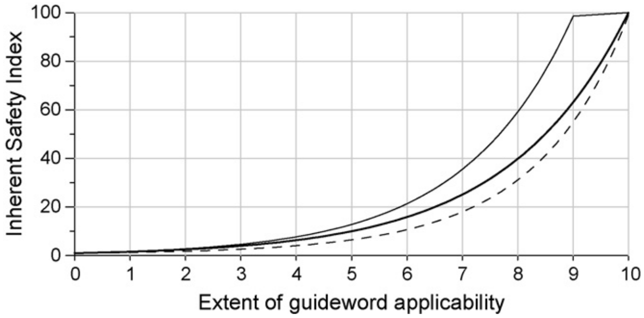

Fig. 3. Inherent safety index for the limitation of effects guideword: limitation of the effects of domino escalation (thin solid line), limitation of the damage potential to target buildings (thick solid line), limitation of the affected area (dashed line).

methodology developed by Khan et al. [32]. Further details on the calculation of DI can be found in the original description of the I2SI methodology [37].

The Process and Hazard Control Index is calculated for various add-on process and hazard control measures that are required or are present in the system. This index is quantified on a scale mutually agreed upon by process safety experts. The index ranges from 1 to 10 for any control arrangement (e.g. temperature control, level control, blast wall, sprinkler system, etc.) and is quantified based on the necessity of this control arrangement in maintaining safe operation for the unit. Again, further details on PHCI can be found in the original description of the I2SI methodology [37].

The Inherent Safety Potential Index is comprised, similarly to the Hazard Index, of two sub-indices: an Inherent Safety Index (ISI) and a Hazard Control Index (HCI). The ISPI for single units is computed as shown in Eq. (4):

$$\mathrm{ISPI} = \frac{\mathrm{ISI}}{\mathrm{HCI}} \tag{4}$$

The ISI is calculated by using scores based on the applicability of the inherent safety guidewords. A detailed description of the procedure for ISI computation in layout assessment is reported in the next section.

The original version of ISPI [37] used *PHCI after the implementation of safety measures* as the denominator in Eq. (4). For layout considerations, the denominator in Eq. (4) is redefined as *HCI* (*Hazard Control Index*) *after the implementation of safety measures*. In the assessment of HCI, the requirement to install further add-on hazard control measures after the previous analysis and implementation of safety measures in the layout option is assessed. Process controls are not considered here, since they are not effective in layout safety. The scores of HCI are evaluated by the same rules as PHCI [37].

2.1.1. *The Inherent Safety Index*

The ISI calculation follows the same procedure as a HAZOP study in which guidewords (in the present case, inherent safety guidewords) are applied to the assessed system. Based on the extent of applicability and the ability to reduce the hazard, an index value is computed for each guideword. *Attenuation*, *simplification* and *limitation of effects* were earlier identified as the relevant guidewords for layout design. For each guideword a specific value of ISI is estimated. For *attenuation* and *limitation of effects* these values are estimated by conversion monograph (Figs. 2 and 3) that relate the quantification of the extent of applicability of the guideword in the assessment option to an ISI score. The extent of applicability was evaluated, in the original I2SI, on a linguistic variable scale resulting from the agreement of a panel of experts [37]. Since the evaluation of the extent of applicability is admittedly subjective, specific guidelines are proposed here to facilitate the quantification of this parameter. These guidelines are discussed in the following paragraphs with respect to each guideword. For the guideword *simplification*, where the current authors experienced objective difficulty in quantifying this subjective parameter, an arbitrary reference table is proposed for the direct assessment of the index value by linguistic guidelines (Table 3).

The specific values of ISI for the single guidewords are combined together to yield the final ISI for the assessed unit, according to Eq. (5):

$$\mathrm{ISI} = [\mathrm{Max}(\eta^2,\ \mathrm{ISI}_\mathrm{a}^2 + \mathrm{ISI}_\mathrm{si} * ||\mathrm{ISI}_\mathrm{si}|| + \mathrm{ISI}_\mathrm{l}^2)]^{1/2} \tag{5}$$

where the subscripts refer to the considered guidewords (a for *attenuation*, si for *simplification* and l for *limitation of effects*). Eq. (5) allows negative values for the simplification parameter, although limiting to $\eta \geq 0$ the lowest value of the final ISI. In the subsequent analysis, the minimum of the ISI range (i.e. η) is set equal to the minimum of HCI ($\eta = 5$). Thus, ISPI will be, for instance, equal to 1 for base case units (i.e. ISI = 5) that do not require any hazard protection device (i.e. HCI = 5).

2.1.1.1. *Attenuation.*

Fig. 2 reports the monograph proposed to convert the extent of applicability of the guideword *attenuation* into an ISI value. This is in accordance with the monograph approach used in the original version of I2SI [37]. The extent of applicability of this guideword is assessed mainly as the ability of the layout option to reduce the hazard potential from domino effects.

To overcome the subjectivity in assessment of the extent of applicability, an approach based on the Domino Hazard Index is used. The DHI is specifically aimed at assessing the domino effect

Table 3
Extended guidelines to decide on the ISI value for the guideword *simplification*

Description	ISI
Process simplified to large extent and hazard eliminated	100
Process simplified to large extent and most significant hazard reduced	90
Process simplified to large extent and hazard reduced	80
Process simplified to large extent and hazard reduced moderately	70
Process simplified and hazard eliminated	60
Process simplified and hazard reduced	50
Process simplified moderately and hazard reduced	40
Process simplified moderately and hazard reduced moderately	30
No significant process simplification and hazard reduced moderately	20
No significant process simplification and no substantial hazard reduction	10
Non-applicable	0
No significant process complication and no substantial hazard increase	−10
No significant process complication and hazard increased moderately	−20
Process complicated moderately and hazard moderately increased	−30
Process complicated moderately and hazard increased	−40
Process complicated and hazard increased	−50
Process complicated and new hazards introduced	−60
Process complicated to large extent and hazard moderately increased	−70
Process complicated to large extent and hazard increased	−80
Process complicated to large extent and hazard significantly increased	−90
Process complicated to large extent and hazard highly increased	−100

hazards caused by a unit in a specific layout. The DHI values for a unit range from 0 to 100. The maximum value means that the unit can affect multiple other units, triggering severe domino consequences; the zero-value indicates no domino possibility from the unit (i.e. the highest degree of inherent safety). Detailed discussion of the index and its development is reported in Part 2 (accompanying paper) of the present work. The DHI of each unit of the layout being assessed is compared with the base option. In this case, the protection provided by passive devices is not accounted for in DHI as the focus is on the domino escalation potential (i.e. hazard) that can be reduced only by inherent measures. The estimation of extent of applicability by DHI may be done using Eq. (6):

$$E_a = \mathrm{Max}\left[0, \left(1 - \frac{\mathrm{DHI_{option}}}{\mathrm{DHI_{base\ option}}}\right) \times 10\right] \quad (6)$$

This proposal to use the rescaled ratio among options of the reference parameter (i.e. DHI) is in line with that suggested in the original I2SI formulation for the assessment of toxicity within the *moderation* guideword (i.e. use of reduction in LC50 values as $\mathrm{LC50_{intial}/LC50_{changed}}$) [37]. The same equation structure will be followed in the subsequent proposals for extent of applicability. In any case, it must be noted that negative values for the extent of applicability are meaningless; thus Eq. (6) yields a minimum E_a equal to zero, in agreement with the range given in Table 2.

2.1.1.2. Simplification. As previously discussed, layout options aiming at safer performance with respect to *attenuation* and *limitation of effects* usually incur an increase in layout complexity. Some important factors that may result in the complexity are:

- Complication of pipe connection among units—The displacing of units from the logical process-flow arrangement makes the piping network, pumping and control more complicated.
- Complication of pipe connection among units—The need for longer pipelines to connect units provides additional sources of release that are not strictly related to the units themselves. Thus, this situation creates additional units (transportation units) that may undergo failure.
- Increase in the number of items in a plant—In addition to the process units, other elements (e.g. blast walls, fire walls, etc.) contribute to the number of items present on the site. As the number of items increases, the requirements for management and maintenance increase, thus complicating procedures and increasing the probability of errors. Moreover, a non-linear disposition of a high number of units and the presence of obstacles (blast walls, dikes, etc.) limit the ease of access to the units. The access limitation further complicates regular operations (e.g. maintenance) as well as emergency response operations (e.g. firefighting).

To assess this complexity introduced by both inherent and passive measures, the former ISI of *simplification* was extended to account for negative values (Table 3). This is based on the idea that complexity can be defined as negation of simplicity. Pursuing *simplification* indeed limits the increase in complexity up to values that are overbalanced by the positive effects from the application of other guidewords.

It is worth remembering that *simplification* is a matter of interrelation among process units; it must be judged not by focusing only on a single unit, but with respect to the whole plant (or occasionally a plant section). The extent of this guideword applicability should be assigned by thinking in terms of unit groups.

2.1.1.3. Limitation of effects. Analysis of the applicability of *limitation of effects* to layout design involves three different elements that must be considered in the assessment: (i) *limitation of the effects of domino escalation* ($\mathrm{ISI_{le}}$), (ii) *limitation of the damage potential to target buildings* ($\mathrm{ISI_{lb}}$), and (iii) *limitation of the affected area* ($\mathrm{ISI_{la}}$). Monographs for converting the extent of applicability of each parameter to an ISI value are defined in Fig. 3, again by an approach in accordance with [37]. These parameters are combined by Eq. (7):

$$\mathrm{ISI_l} = \mathrm{Min}\{100,\ [(\mathrm{ISI_{le}})^3 + (\mathrm{ISI_{lb}})^3 + (\mathrm{ISI_{la}})^3]^{1/3}\} \quad (7)$$

Also in this case, suggestions are provided for guidance in the evaluation of extent of applicability, striving to reduce the degree of subjectivity in the analysis:

(i) *Limitation of the effects of domino escalation* can be estimated by resorting to the Domino Hazard Index as a reference. The approach is similar to that followed for *attenuation*, but the focus, as discussed earlier, is different in this case. In *limitation of the effects of domino escalation*, the DHI is calculated considering the synergistic effect of passive and inherent measure protection on domino consequence limitation. Similar to Eq. (6), the extent of applicability of *limitation of the effects of domino escalation* may be evaluated using Eq. (8):

$$E_{le} = \mathrm{Max}\left[0, \left(1 - \frac{\mathrm{DHI_{option}}}{\mathrm{DHI_{base\ option}}}\right) \times 10\right] \quad (8)$$

(ii) *Limitation of the damage potential to target buildings* aims to assess the location of the facility's populated buildings (control rooms, laboratories, workshops, offices, etc.) in relation to the hazardous units of the process. A proposal for guiding this assessment is based on the grouping of the buildings into hazard-susceptible areas (i.e. areas affected by fire, explosion and acute toxic effects). The assessment has to take into account the combined effect of different primary units on the same building, since they may change from one layout option to another. Thus a reference index (A_j) is calculated for each target building (j) according to Eqs. (9) and (10):

$$a_{i,j} = \mathrm{Max}\left(1 - \frac{D_{i,j}}{B_i};\ 0\right) \quad (9)$$

$$A_j = \sum_i a_{i,j} \quad (10)$$

where $D_{i,j}$ is the distance between the ith unit and the jth building, and B_i is the maximum damage distance of the ith unit for fire, explosion and acute toxic effects. The estimation of extent of applicability of $\mathrm{ISI_{lb}}$ is defined by Eq. (11):

$$\text{if } a_{i,j,\mathrm{option}} > 0 \text{ or } a_{i,j,\mathrm{base\ option}} > 0 \quad (11)$$

than

$$E_{lb,i} = \mathrm{Max}\left[0, \left(1 - \frac{\sum_j A_{j,\mathrm{option}}}{\sum_j A_{j,\mathrm{base\ option}}}\right) \times 10\right]$$

otherwise

$$E_{lb,i} = 0$$

(iii) *Limitation of the affected area* accounts for the effects of passive measures to decrease the area susceptible to dangerous consequences, no matter if particular structures are located there (e.g. units or buildings), but simply because final targets (e.g. people, environment) can potentially be present. The suggested guideline for quantitative assessment of this aspect is based on the percentage decrease of damage area compared to the same unit in the base option:

$$E_{\mathrm{la}} = \mathrm{Max}\left[0, \left(1 - \frac{\mathrm{AA}_{\mathrm{option}}}{\mathrm{AA}_{\mathrm{base\ option}}}\right) \times 10\right] \qquad (12)$$

where AA is the affected area exposed to the consequence from the considered unit (e.g. if no protective devices exist, this is the area encompassed by the damage radius; if protective devices exist, the upwind protected areas are subtracted).

2.2. Cost indexing

The cost indexing procedure of I2SI accounts for and evaluates the economic aspects of inherent safety. The costing system (right-hand side of Fig. 1) is comprised of two sub-indices: a conventional safety cost index (CSCI) and an inherent safety cost index (ISCI). A further index specific to layout analysis, the Loss Saving Index (LSI), is introduced to account for the savings on potential losses due to a reduction of domino escalation possibility.

2.2.1. Conventional safety cost index

The conventional safety cost index is computed as shown in Eq. (13):

$$\mathrm{CSCI} = \frac{C_{\mathrm{ConvSafety}}}{C_{\mathrm{Loss}}} \qquad (13)$$

The numerator in Eq. (13), $C_{\mathrm{ConvSafety}}$, is the sum of the costs of process control measures and add-on (end-of-pipe) safety measures (i.e. $C_{\mathrm{ConvSafety}} = C_{\mathrm{Control}} + C_{\mathrm{Add\text{-}on}}$). It can be estimated by the number of measures required and their representative reference costs (see e.g. Khan and Amyotte [16]).

The denominator in Eq. (13), C_{Loss}, represents the dollar value of expected losses caused by accidental events in a unit. It is comprised of five components, as shown in Eq. (14):

$$C_{\mathrm{Loss}} = C_{\mathrm{PL}} + C_{\mathrm{AL}} + C_{\mathrm{HHL}} + C_{\mathrm{ECC}} + C_{\mathrm{DEC}} \qquad (14)$$

Production Loss (PL) is the economic consequence of production shutdown (i.e. business interruption). Direct Asset Loss (AL) represents the value of the physical unit itself which is depleted by the accidental event (e.g. fire or explosion). Human Health Loss (HHL) is calculated in terms of the cost of fatalities/injuries directly caused by the accident at the unit. The current authors acknowledge that there can be a high degree of subjectivity and discomfort associated with assigning a dollar value to fatality and/or injury. While the value of a human life is immeasurable, it is still possible to employ indicators such as insurance costs, rehabilitation costs, worker compensation rates, etc. Environmental Cleanup Cost (ECC) is associated with the mass or volume of soil, water and air that were contaminated by the accidental event. Reference costs for the estimation of this parameter are adapted from [16,44]. Domino Escalation Cost (DEC) is a cost term explicitly introduced in the present approach to account for the loss consequences of the possible chain of accidents. It represents the sum of the loss related to the secondary units involved, weighted by a parameter that features the probability of being involved, as expressed by Eq. (15):

$$C_{\mathrm{DEC}} = \sum_k s_k (C_{\mathrm{AL},k} + C_{\mathrm{HHL},k} + C_{\mathrm{ECC},k}) \qquad (15)$$

where $C_{\mathrm{AL},k}$, $C_{\mathrm{HHL},k}$ and $C_{\mathrm{ECC},k}$ are, respectively, the additional direct asset loss, human health loss and environmental cleanup costs for the failure of each kth secondary unit, as a result of escalation from the primary unit under assessment. The production loss cost is not accounted for a second time in C_{DEC} because the target units are considered to be in the same production line as the primary unit. The factor s_k accounts for the credibility that the failure of the considered unit affects the kth secondary unit. It can be evaluated as a function of the maximum Domino Hazard Score ($\mathrm{DHS}_{i,k}$), an intermediate index in the DHI calculation (see Part 2, accompanying paper). The correlation between s_k and $\mathrm{DHS}_{i,k}$ is reported in Fig. 4.

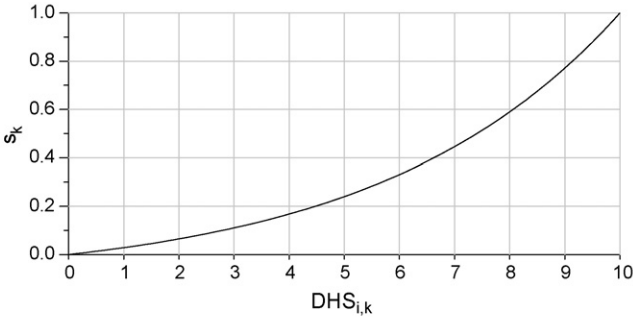

Fig. 4. Credit factor for domino escalation as a function of $\mathrm{DHS}_{i,k}$.

2.2.2. Inherent Safety Cost Index

The inherent safety cost index is computed by Eq. (16):

$$\mathrm{ISCI} = \frac{C_{\mathrm{InhSafety}}}{C_{\mathrm{Loss}}} \qquad (16)$$

The denominator in Eq. (16), C_{Loss}, is the same as in Eq. (13) for the CSCI. However, the numerator, $C_{\mathrm{InhSafety}}$, is the sum of the costs of inherent safety implementation, of process control measures, and of add-on (end-of-pipe) safety measures still required in the inherently safer layout option (i.e. $C_{\mathrm{InhSafety}} = C_{\mathrm{Inherent}} + C_{\mathrm{Control}} + C_{\mathrm{Add\text{-}on}}$). The costs of process control and add-on safety measures are calculated following the same procedure as for CSCI.

The costs for inherent safety implementation are estimated considering the extent of application of the inherent safety guidewords and the costs associated with their application. A marginal cost (i.e. capital cost difference of the assessed option relative to the base case) is calculated for the application of each guideword. For example, the cost of extra space required for increased unit segregation is estimated and referred to as the cost of implementing the guideword *attenuation*, as earlier discussed. This cost is divided by a factor called the extent of applicability, which denotes the extent to which the guideword will eliminate/reduce the hazards. Hence, the total cost of inherent safety implementation is represented by Eq. (17):

$$C_{\mathrm{Inherent}} = \frac{C_{\mathrm{a}}}{E_{\mathrm{a}}} + \frac{C_{\mathrm{si}}}{E_{\mathrm{si}}} + \frac{C_{\mathrm{l}}}{E_{\mathrm{l}}} \qquad (17)$$

where the C variables are the costs and E the extents of applicability of, respectively, *attenuation* (a), *simplification* (si), and *limitation of effects* (l).

2.2.3. Loss Saving Index

The possibility of escalation by domino effects, assessed by C_{DEC}, is frequently a prevailing term within the cost of loss. This value can have significant variation for different layout options because of the choices specifically aimed at inherent safety improvement. A new index is proposed to map out the economic effect of escalation reduction deriving from inherently safer layout design:

$$\mathrm{LSI}_{\mathrm{option}} = \frac{C_{\mathrm{InhSafety,option}} + (C_{\mathrm{Loss,option}} - C_{\mathrm{loss,base\ option}})}{C_{\mathrm{loss,base\ option}}} \qquad (18)$$

This index compares inherent safety costs with a parameter that represents the savings from avoided loss by domino escalation, since it considers loss variations between the base case and assessed options.

3. Conclusion

Layout plays a key role in defining the safety of a process plant. The likelihood of the various hazardous units interacting with one another and with possible damage targets is strongly influenced by choices made with respect to layout design. In particular, the hazard of chain effects (domino effect) leading to catastrophic consequences by escalation can be limited by proper design strategies aimed at improving the inherent safety of the plot. An attempt to bring inherent safety into layout design has been presented in the current paper. A novel indexing approach was developed to guide inherently safer choices in the early phases of layout design.

The proposed tool is based on the former framework of I2SI assessment [16,37] in order to produce a common approach for both process and layout assessment. Moreover the ability of the I2SI approach to integrate the assessment of inherent safety guideword application, unit hazards, control measure effects, and safety economics was exploited in the present tool.

A review of the inherent safety guidewords identified *attenuation*, *simplification* and *limitation of effects* as the ones applicable within the constraints of a typical layout design. The former subindices of I2SI were updated to account for the specific features related to these guidewords in layout assessment. In particular, reference indices were proposed to reduce the subjectivity in the definition of guideword applicability. Among these indices, the Domino Hazard Index accounts, in a simple but consequence-driven way, for the complex interactions involved in domino escalation.

The proposed method is meant to provide a guide in the early phases of layout design, where the major choices influencing inherent safety can be effectively undertaken. This does not eliminate or replace the need for further detailed safety analysis in later stages, where more detailed information on the nature of the hazards present is available. The current authors are aware of the intrinsic level of subjectivity implied in some aspects of the proposed approach. However, considering the limited data of early design stages and the need for quick assessment tools, the proposed method represents a positive effort to face the challenges of inherent safety implementation in layout design.

Nevertheless additional work can be done to further improve the method by minimizing the biases possibly introduced by subjective judgment and to encompass additional safety aspects. Moreover, a proactive procedure should be developed to support decision making in design. Our research group is actively involved in conducting such efforts.

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