Delft University of Technology

Techno-Economic Analysis of Protection Barriers Against Fire-Induced Domino Effects in the Chemical and Process Industry

Valente, Matteo; Reniers, Genserik; Cozzani, Valerio

DOI
10.1016/j.ress.2025.111646

Publication date
2025

Document Version
Final published version

Published in
Reliability Engineering and System Safety

Reliability Engineering and System Safety 266 (2026) 111646

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Techno-Economic Analysis of Protection Barriers Against Fire-Induced Domino Effects in the Chemical and Process Industry

Matteo Valente [a], Genserik Reniers [b,c,d,*], Valerio Cozzani [a]

[a] LISES -Laboratory of Industrial Safety and Environmental Sustainability, Department of Civil, Chemical, Environmental and Material Engineering, University of Bologna, via Terracini 28, 40131, Bologna, Italy
[b] Faculty of Technology, Policy and Management, Safety and Security Science Section, TU Delft, Delft, the Netherlands
[c] Faculty of Applied Economics, Antwerp Research Group on Safety and Security (ARGoSS), University Antwerp, Antwerp, Belgium
[d] CEDON, KULeuven, Campus Brussels, Brussels, Belgium

ARTICLE INFO

Keywords:
Domino effect
Safety barriers
Fire Protection Barriers
Escalation
Cascading scenarios
Cost-Effectiveness Analysis
Cost Variable Decision Tree

ABSTRACT

Domino effects triggered by fire are responsible for most of the cascading accidents which occurred in the chemical and process industry. Their occurrence is highly dependent on the performance of fire protection barriers, as well as on the primary fire scenario. Active and passive safety barriers are largely used to prevent or mitigate domino effects. However, a blinkered allocation approach of safety measures based on a subjective strategy, which does not consider cascading effects possibly triggered by an accident, can lead to a deployment of a safety plan that is not effective in effectively mitigating the consequences of a domino accident. In the present study, an innovative methodology supporting and optimizing the decision-making process for fire prevention in a chemical site has been developed. The methodology provides an optimal allocation of safety measures, aimed at preventing and mitigating fire escalation under budget constraints. A Cost-Effectiveness Analysis with an optimization algorithm is used to allocate a limited budget in terms of fire safety barriers. A novel tool, named Cost Variable Decision Tree, has been developed to support fire prevention investment decisions. The methodology is able to assess the economics of safety plan implementation, considering both the costs of safety measures and the hypothetical benefits deriving from avoided accidents. An illustrative case-study was carried out, confirming that the proposed methodology can effectively support the decision-making process addressing safety barriers allocation.

1. Introduction

Domino effects in the chemical and process industries have received growing attention in the scientific and technical literature, due to the growing public concern caused by such High-Impact Low Probability accident scenarios (HILP) [1]. Also, the increasing complexity and interdependencies in chemical industrial plant cause the storage and transport infrastructure, such as storage tanks and pipework, even more vulnerable to domino effects [2,3]. Due to the potentially catastrophic consequences of escalation scenarios, a specific assessment of domino effect is required by several technical standards and regulations, as the European Seveso-III Directive [4].

Every year, industrial fire accidents resulting in domino effects cause massive asset damage resulting in billions of Euros of economic losses [5,6]. Actually, more than half of the industrial accidents resulting in domino effects occurred between 1961 and 2010 involved fire scenarios as the primary event [1,7,8]. In these accidents, the escalation vector triggering domino effect is usually heat radiation, and the secondary targets affected are mostly atmospheric and pressurized storage tanks. Notably, severe domino accidents may be triggered when the thermal radiation impact on several target units, leading to high-level domino accidents [9]. A peculiar aspect of domino effects triggered by fire is that escalation is usually delayed with respect to the initiating event [1,10]. Actually, a time interval, ranging from few minutes to several hours, usually exist before the temperature of the shell becomes critical for the structural integrity. Also, during this period, the rising temperature of the fluid may lead to the increase of the internal pressure of the tank, contributing to compromising its structural integrity [11,12]. This time lap, lasting since the start of the primary fire until the failure of the target equipment leading to a loss of containment, is generally termed "time to failure" (*ttf*) [1,13,14].

* Corresponding author.
E-mail address: G.L.L.M.E.Reniers@tudelft.nl (G. Reniers).

https://doi.org/10.1016/j.ress.2025.111646
Received 7 May 2025; Received in revised form 8 August 2025; Accepted 31 August 2025
Available online 1 September 2025

Nomenclature

C_{BUDGET}	Budget constraint
CER_i	Cost-effectiveness ratio associated to the implementation of the *i-th* safety measure
C_i	cost of the *i-th* safety measure
C_{TOT}	Total cost of the safety plan
ΔE	Percent decrease of the overall escalation factor
E	Overall escalation factor
E_0	Overall escalation factor of the baseline scenario
$E_{new,i}$	Overall escalation factor updated considering the implementation of the i-th safety measure
$f_{esc,i}$	Escalation frequency of the *i-th* primary fire with respect to the *t-th* target equipment
$f^t_{esc,i}$	Overall escalation frequency of the *i-th* primary fire with respect to the *t-th* target equipment
$f_{LOC,i}$	Frequency of the LOC causing the *i-th* primary fire
$f_{pf,i}$	Frequency of the *i-th* primary fire
g	Gravitational acceleration
η	Safety barrier effectiveness
PFD	Probability of failure on demand of a safety barrier
P_d	Death probability of a domino accident
$P_{d,i}$	Death probability of the contemporary scenario *i-th* in a domino accident
$P_{ig,i}$	Ignition probability of the *i-th* primary fire
P_j	Probability of the *j-th* combination of events
$P_{j,i}$	Probability of the *i-th* event in the *j-th* combination
$P^t_{j,i}$	Probability of the *j-th* secondary with respect to the *i-th* primary and the *t-th* target equipment
$P^t_{esc,i}$	Escalation probability of the *i-th* primary fire with respect to the *t-th* target equipment
$P_{esc,i}$	Escalation probability of the *i-th* primary fire
RU	Relative humidity
T_{amb}	Ambient temperature
tem	Time for the effective mitigation
ttf	Time to failure
ρ_{air}	Air density

Acronyms

BS	Baseline Scenario
CBA	Cost-Benefit Analysis
CEA	Cost-Effectiveness Analysis
CEAO	Cost-Effectiveness Analysis & Optimization
CVDTA	Cost Variable Decision Tree Analysis
CVDT	Cost Variable Decision Tree
ETA	Event Tree Analysis
FE	Fire Escalation
FEA	Fire Escalation Analysis
FC	Fireproofing Coating
HILP	High-Impact Low Probability
LOC	Loss of Containment
LPG	Liquified Propane Gas
LSF	Large Scale Fire
MIMAH	Major Accident Hazards
NES	No Escalation Scenario
QRA	Quantitative Risk Analysis
SP	Safety Plan
VSL	Value of Statistic Life
WDS	Water Deluge System
WSS	Water Sprinkler System

In case an inherent safety design is not possible, safety barriers may be used to mitigate the consequences and protect secondary targets, avoiding domino effect [15–17]. According to the classification of protection layers proposed by CCPS [18,19], safety barriers may be divided in three different categories: (i) active protection systems; (ii) passive protection systems; (iii) procedural and emergency measures. Safety barriers have a key role in the prevention of fire escalation. Indeed, they can prevent or delay the failure of the target equipment for a time sufficient for emergency response, aimed at the mitigation or suppression of the primary fire. The time needed to deploy emergency response by internal and/or external teams [20] clearly depends on their level of preparedness and it is typically estimated based on the time to detect the hazard and alert emergency teams, to initiate pre-planned fire containment or mitigation actions, and to implement effective external intervention [21]. In general, if the total emergency response time, referred to as the "time for effective mitigation" (*tem*), is shorter than the time to failure (*ttf*) of the target equipment, fire escalation can be prevented [1].

A method for quantifying the performance of safety barriers was proposed by Landucci et al. [22]. The approach may also be used to support the allocation of safety barriers based on cost and on performance criteria. Actually, the possibility of developing a performance-based methodology for safety barriers allocation (e.g., [23–26]) may allow avoiding the use of simplistic rules of thumb, which often lead to a subjective and uncertain decision-making process [27]. However, in industrial practice, budget constrains also need to be considered, thus the resources allocated for the protection of a specific target are not available for others. Therefore, the development of performance-based allocation approaches of safety barriers and safety systems is crucial to make the most effective use of the available budget, having a positive impact on the effectiveness of prevention policies implemented by chemical companies [28].

When it comes to the assessment of safety investments, economic issues related to hypothetical benefits of avoided accidents cannot be overlooked [29]. Sometimes, decision makers opt for budget cuts and safety downsizing since they are responsible only for a brief period for safety budgets allocations, and the accident probabilities are extremely low [30]. In such scenarios, managers tend to reduce short-term real costs rather than to make decisions leading to long-term hypothetical benefits (related to avoided accidents). However, when a long-term perspective is adopted, safety investments definitely have a positive impact on company profitability. The benefits of a safety investment can be estimated considering the difference in losses with and without a safety investment, also taking into account the difference in the likelihood of accidents. In the literature, several authors addressed the description of conceptual foundation and methods to quantify the benefits associated with of safety investments for accident prevention [30–32]. Specifically, in a recent literature review, Van Coile et al. [33] examined several approaches and methodologies proposing cost-benefit analysis in the field of fire safety science, identifying the key principles that characterize these analyses.

Concerning the chemical and process industry, in 2015 Necci et al. [34] highlighted that only few studies focused on innovative safety management tools for domino accidents. Indeed, the aim of more recent studies, mainly published in the last decade, is the management of risk caused by domino effects, which mostly aims to prevent and mitigate such accidents by implementing safety barriers [35–38]. These studies applied common tools used in the Quantitative Risk Analysis (QRA) of Seveso sites for the development of specific risk management approaches, aiming to identify industrial installation where safety barriers would be more effective in preventing or mitigating escalation sequences. These safety management approaches, mainly based on risk reduction, provide a substantial contribution in managing possible domino effects. However, they overlook economic issues. As the implementation of safety measures necessitates financial investment, the decision-making process requires to assess whether the benefits of implementing particular safety measures justify the costs involved.

Several studies proposed economic models and optimization methods which take into account both protection costs and potential avoided losses [25,39–42]. These studies aim at developing methodologies to prioritize safety investments considering the potential impact on the overall safety of the company operations, and they are mainly based on the implementation of Cost-Effectiveness Analyses (CEA) or Cost-Benefit Analyses (CBA). While CBA evaluates whether the monetary value of the expected benefits exceeds the associated costs, CEA focuses on identifying the most efficient way to achieve a specific safety outcome by comparing the cost per unit of effectiveness (e.g., risk reduction) [43]. Especially in the chemical and process industry, the main challenge in CBA approaches lies in the possible incompleteness and high uncertainty associated with estimating hypothetical benefits, such as avoided accidents or damages, which are influenced by numerous variables and assumptions [30,31].

In order to prevent the uncertainties associated with the assessment of hypothetical benefits from influencing the solution of the allocation problem, CEA approaches may be preferred and coupled with complementary decision assessment tools to support the evaluation of the hypothetical benefits associated with safety investments [27,30]. Thus, even if the economic assessment of hypothetical benefits is affected by uncertainty, this does not affect the allocation problem, since the economic assessment is performed only at a following step. Specifically, decision tree analysis is among the most widely adopted approaches to evaluate the potential consequences of alternative safety choice and to support decision making process [44–46]. In the literature, a specific approach named Cost Variable Decision Tree Analysis (CVDTA) is proposed as a valuable analysis to support decision making process when a decision may lead to different alternative outcomes [27,30], helping decision makers to evaluate the potential consequences of their choices. This characteristic is extremely effective in the economic assessment of cascading scenarios with multiple potential outcomes, where the outcomes are uncertain and thus characterized by probabilities of occurrence. Moreover, differently from CEA and CBA, the CVDTA clearly shows to the decision makers the preventive and mitigating effects of the safety investment in the domino accident pathway [30]. However, a methodology to develop this analysis for assessing the effectiveness of safety investments for the prevention of fire induced domino effects is still not present in the literature.

In order to fill the above gap, in the present study an innovative methodology that enhances and streamlines the decision-making process for fire escalation was developed. The methodology aims at incorporating the costs of safety measures as well as the potential benefits resulting from preventing accidents, thereby optimizing the decision-making process. A cost-effectiveness optimization model was adopted, specifically tailored to address the allocation problem under budget constraints. A heuristic algorithm, based on a means-end analysis problem-solving technique [47], was developed to facilitate efficient allocation of safety measures. A specific methodology based on the CVDTA was developed to evaluate the investment viability of the resulting set of Pareto solutions obtained from the allocation problem. Thus, the novel approach proposed allows the assessment of the viability of the investment considering the hypothetical benefits of avoided accidents.

In the following, the novel methodology developed in this study is presented in Section 2. To illustrate its application, a case study is provided in Section 3. Section 4 addresses the discussion of the results. Finally, conclusions are drawn in Section 5.

2. Methodology

The proposed methodology integrates an optimization model based on CEA with a CVDTA to improve decision-making in fire prevention, merging an effective deployment strategy for safety barriers and an economic assessment of the investment viability.

Figure 1 shows the outline of the methodology developed to support the decision-making process concerning the introduction of safety measures to prevent or mitigate fire escalation. As shown in the figure, the methodology is divided in three parts: (i) Fire Escalation Analysis (FEA), (ii) Cost-Effectiveness Analysis & Optimization (CEAO) and (iii) Cost Variable Decision Tree Analysis (CVDTA).

The preliminary phase of the procedure requires to gather all the key data needed to perform each of the three steps in the methodology. These include all the necessary information required by the model to calculate escalation probabilities and to assess the potential consequences of accidents. In addition to technical data, economic data should also be collected, as it is crucial for evaluating both the financial impact of preventive measures and the consequences of accidents. Table 1 summarizes the input data required for the application of the methodology.

The first step of the methodology (i.e., FEA) has the aim to carry out a systematic assessment of all fire scenarios leading to escalation and to define the escalation paths in the system analysed. This is of fundamental importance to identify, in step 2 of the methodology, the suitable measures to deal with fire escalation and to build the initial portfolio of safety barriers to be consider for the cost-effective allocation.

Eventually, the first step of the methodology aims at assessing the fire escalation potential in the area of interest of the analysis for the baseline scenario, using the escalation probabilities associated to all the primary fires identified. Then, the probabilities are used to calculate the overall escalation factor for the base line scenarios (E_0), that serve as a reference point to evaluate the effectiveness of safety barrier allocation in the step 2 of the methodology. Specifically, the escalation factor is calculated as the sum of the frequencies with which each single equipment can be involved in the first level of escalation of the identified primary fires (see Section 2.1).

In the second step of the methodology (i.e., CEAO) the additional safety measures that can be added to the baseline safety plan to prevent and mitigate possible domino effects are identified. Then, a CEA coupled to a heuristic optimization algorithm is used to solve the safety measures allocation problem. Starting from safety criteria and the company budget constraints concerning safety investments, the analysis provides an optimal allocation of the safety measures available for fire prevention.

Notably, the heuristic optimization algorithm developed falls in the class of greedy algorithms since it involves partitioning the overall allocation problem into smaller sub-problems that makes the locally optimal choice at each step to find a global optimum.

The third step of the methodology (i.e., the CVDTA) consists in the development of a Cost Variable Decision Tree (CVDT) based on the results of the allocation algorithm. The decision tree has the aim to highlight the economic benefit for the company associated to the implementation of the optimal safety plan. An economic assessment of the consequences is performed in this step, estimating the monetary value of all costs associated with the escalation of the fire scenarios.

The three steps of the methodology are described in detail in the following sections.

2.1. Fire Escalation Analysis

As shown in Figure 2, in this step of the methodology all the potential primary fires within the system of interest and the possible escalation targets are identified. An overall escalation factor is then calculated.

In step 1.1 of the methodology (see Figure 2), all relevant equipment items susceptible to generate fire scenarios need to be identified. In this study, the relevant fire sources are selected adopting the approach proposed in the Methodology for the Identification of Major Accident Hazards (MIMAH) [48] as the procedure is sufficiently general and can be adapted to site-specific thresholds. First, equipment items processing

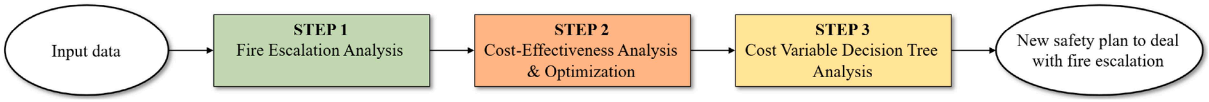

Figure 1. Flow chart of the methodology.

Table 1
Summary of the input data required for the application of the methodology. LOC: Loss of Containment; η: safety barrier effectiveness; PFD: probability of failure on demand of a safety barrier.

Information related to	Information needed
Equipment	Number of equipment items present in the area of interest Type of equipment item (pressurized/ atmospheric, storage/process vessel, etc.) Size and shape (cylindrical/ spherical) of the equipment items Filling degree Fire mitigation systems (firefighting systems, etc.) Position of the equipment (X, Y coordinates)
Substance	Operating/storage conditions (temperature and pressure) Category of the substance according to the CLP Regulation Phase Mass inventory
LOCs	Characterization of LOCs associated to each equipment item
Meteorological conditions	Ambient temperature, solar heat radiation flux, ambient relative humidity Wind direction and speed, category of atmospheric stability
Human and assets	Number of persons present in the area Location of buildings/offices (X, Y coordinates)
Models for consequence and vulnerability analysis	Source term models Consequence analysis models Vulnerability (Probit) models
Safety systems/measures	Safety systems/measures considered PFD, η
Cost	Cost of safety measures Meta-data to calculate accident cost Available budget

or storing flammable, highly flammable or extremely flammable substances (according to CLP regulation [49]) are identified as potentially hazardous equipment. Next, if the mass of flammable substance in the equipment is higher or equal to a threshold value the equipment item is classified as a relevant hazardous equipment. Specific threshold values are suggested in the literature [48,50], based on the properties of the substances, their physical state, and their location in relation to other hazardous equipment. Thresholds adopted in the present study are reported in Section 1 of the supplementary material.

In step 1.2 (see Figure 2), credible release scenarios for each equipment items selected in the previous step are identified and characterized. Several publications suggest baseline release scenarios for different equipment items [48,50]. In the illustrative case-study carried out, Loss of Containment (LOC) events suggested by the Purple Book [50] are applied (see Section 2 of the supplementary material).

Different models are available to carry out the characterization of the LOC intensity and the final consequences of the release [20]. In the case-study carried out, the integral models proposed in the Yellow Book [51] were applied. However, alternative models may as well be used to carry out this task and obtain phase, mass flow rate, size, and orientation of the release.

In step 1.3, (see Figure 2) the frequency for each possible primary fire scenario is assessed. Therefore, for each LOC scenario identified in the previous step, the event tree associated with the specific release is identified and the corresponding possible primary fire end-point scenarios are determined. Since the aim of the present methodology is to develop a safety plan to prevent fire escalation, only fire end-point scenarios were considered (i.e., jet fires, pool fires, fireballs and flash fires). Then, for each LOC scenario identified previously, the possible primary fire frequencies are determined, considering the probability of direct and delayed ignition.

In the illustrative case study presented in Section 3 the baseline values for the LOC frequencies proposed in the Purple Book [50] are adopted (see Table S3 in the supplementary material). Nevertheless, although for the assessment of the frequencies of the primary scenarios baseline failure frequency values may be obtained from specific database, fault tree analysis can be applied as well [48].

Data concerning the probability of direct and delayed ignition may be obtained from different sources (e.g. see [48,50,52]). In the case-study carried out in the following, the values proposed by the Purple Book [50] were adopted (see Section 3 in the Supplementary Material).

In step 1.4 (see Figure 2), the possible secondary escalation targets are identified. The identification of target equipment may be carried out comparing the radiation values to threshold criteria for escalation. In the present study, the threshold criteria proposed by Cozzani et al. [53] and Antonioni et al. [54] were used to carry out the case-study (see Table S5 of the Supplementary Material).

The physical effects (radiation intensity) caused by the primary fires are then assessed using conventional literature models, as those proposed by the Yellow Book [51].

In step 1.5 (see Figure 2), the escalation probability and the escalation frequency of each primary fire (i.e., frequency of the primary fire multiplied by its escalation probability) are calculated considering each of the secondary targets identified, using a specific event tree analysis (ETA) [22], addressing the assessment of escalation scenarios also taking into account the effect of safety barriers.

This methodology adopts specific operators for the identification of the possible alternative secondary events following either barriers activation or failure proposed by Landucci et al. [55]. Two key parameters are used to evaluate the performance of the active and passive barriers in reducing the escalation probability [21]: (i) the Probability of Failure on Demand (PFD), and (ii) the Effectiveness (η) defined as the probability that the safety barrier, once successfully activated, is able to prevent the escalation. If the effect of safety barrier is considered there are three possible outcomes associated with a generic equipment involved in a domino chain: i) no escalation; ii) mitigated escalation events; iii) unmitigated escalation events. For sake of clarity an example of event tree provided by the procedure is provided in Figure 3, while the logical operators used to consider the intermediate event are described in Table 2.

The use of specific fragility models is needed in the vessel fragility gate to assess the damage probability (P_d in Table 2) of the target equipment, and thus the escalation probability of the primary fire once the effects of safety barrier is considered [22]. Table S7 in the Supplementary Material reports the fragility models used to carry out the case-study. Also in this case, the physical effects may be calculated by conventional literature models [51]. As suggested form Alileche et al. [56], "cut-off levels" for the escalation probability may be defined to limit the analysis to relevant escalation scenarios and reduce the computational effort as well.

In step 1.6 (see Figure 2), an overall fire escalation factor (E) is calculated for the facility of interest. This parameter is used as an indicator of the fire escalation risk, in order to obtain a quantitative

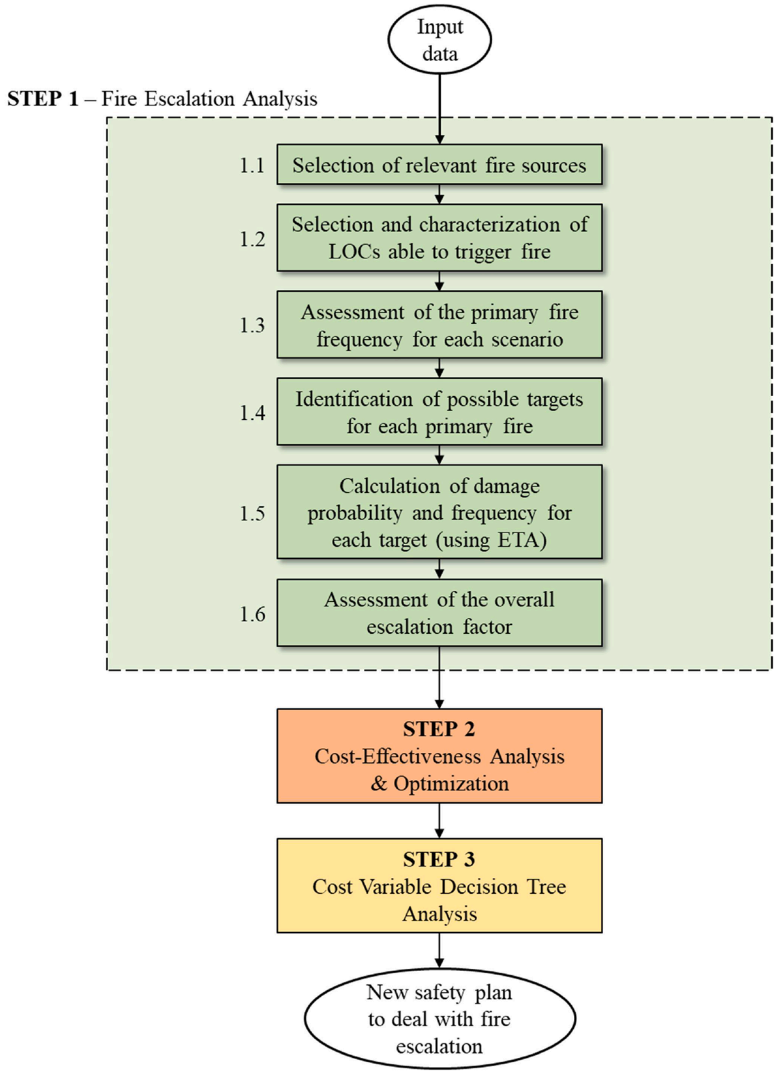

Figure 2. Flow chart of the step 1 of the methodology (LOC: Loss of Containment; ETA: Event Tree Analysis).

assessment of the effectiveness deriving from the introduction of safety systems and safety barriers.

As mentioned above, in the ETA applied, when a target equipment is involved in escalation scenarios, several different outcomes may occur, based on the number of safety barriers available and/or effectively activated (e.g., unmitigated scenarios, mitigated scenarios, no escalation). Therefore, the escalation probability for a primary fire is assessed taking into account both unmitigated and mitigated secondary fire. Considering the alternative scenarios in the event tree as disjoint events, the escalation probability of a primary fire with respect to the *t-th* target equipment, $P^t_{esc,i,}$ is calculated as follows:

$$P^t_{esc,i} = \sum_{j=1}^{h} P^t_{j,i} \tag{1}$$

where $P^t_{j,i}$ is the probability of the *j-th* secondary event in which an escalation of the *i-th* primary fire takes place with respect to the *t-th* target equipment, and *h* is the number of the possible escalation scenarios.

The overall escalation frequency of the *i-th* primary fire with respect to the *t-th* target equipment, $f^t_{esc,i}$, can thus be calculated as:

$$f^t_{esc,i} = f_{pf,i} \cdot P^t_{esc,i} = \left(f_{LOC,i} \cdot P_{ig,i}\right) \cdot P^t_{esc,i} \tag{2}$$

Where $f_{pf,i}$ is the frequency of the *i-th* primary fire, $f_{LOC,i}$ is the frequency of the LOC causing the *i-th* primary fire, and $P_{ig,i}$ the ignition probability, which can be delayed or immediate.

The identification of the possible escalation paths is fundamental to identify, in step 2 of the methodology, a portfolio of the potential safety measures. Also, in order to carry out the allocation of safety measures based on a cost-effectiveness criterion, a reference parameter representing the fire escalation potential has to be calculated. Therefore, the overall escalation factor, E_0, is determined by considering the frequencies with which each target equipment can be involved in the first level of escalation triggered by identified primary fires:

$$E_0 = \sum_{t=1}^{n} \sum_{i=1}^{m_t} f^t_{esc,i} \tag{3}$$

where E_0 is the baseline overall escalation factor, $f^t_{esc,i}$ is the escalation frequency of the *i-th* primary fire with respect to the *t-th* target equipment, *n* is the total number of target equipment affected by primary fires identified, and m_t is the total number of primary fires where the *t-th* equipment is involved as target. In Eq. 3, the inner summation evaluates the overall escalation frequency for each target equipment, while the outer summation aggregates these frequencies into a single parameter. In the assessment of the probability of fire escalation scenarios, both active and passive barriers present in the system shall be considered.

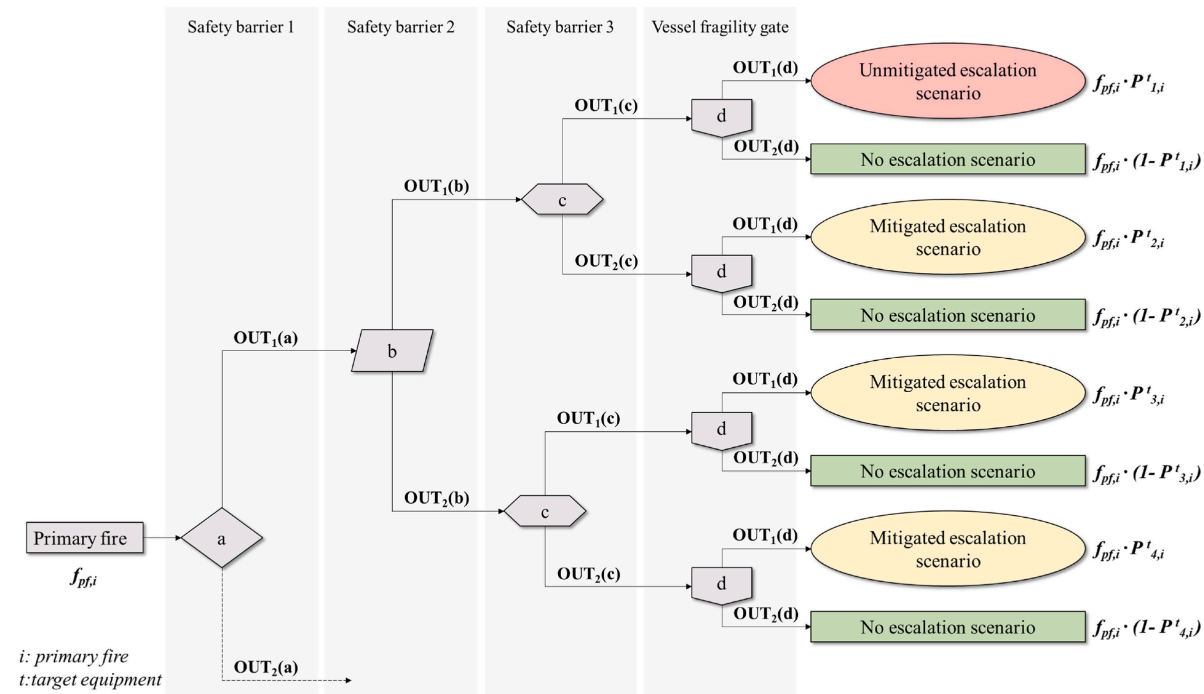

Figure 3. Example of event tree to support the identification and assessment of unmitigated and partially mitigated scenarios, taking into account the effects of safety barriers. Adapted from Landucci et al. [21,55].

Table 2
Definition of operators and gate types used in the ETA to identify and assess unmitigated and partially mitigated scenarios [21,55].

Gate	Graphical representation	Description
a	$OUT_1 = IN \times [PFD + (1-\eta) \times (1-PFD)]$; $OUT_2 = IN \times (1-PFD) \times \eta$	Simple composite probability: availability, expressed as the probability of failure on demand, is multiplied by a single probability value expressing the probability of barrier success in the prevention of the escalation.
b	$OUT_1 = IN \times [PFD + (1-\eta) \times (1-PFD)]$; $OUT_2 = IN \times (1-PFD) \times \eta$	o m o ite ro a ility di tri ution (gate ty e " "): a aila ility, ex pressed as the probability of failure on demand, is multiplied by a probability distribution expressing the probability of barrier success in the prevention of escalation, thus obtaining a composite probability of barrier failure on demand.
c	$OUT_1 = IN \times PFD$; $OUT_2 = IN \times (1-PFD) \times (1-\eta)$; $OUT_3 = IN \times (1-PFD) \times \eta$	i rete ro a ility di tri ution (gate ty e " "): de ending on arrier effectiveness, three or more events may originate from the gate describing barrier performance.
d	$OUT_1 = IN \times P_d$; $OUT_2 = IN \times (1-P_d)$	Vessel fragility gate: based on the status of the target equipment (e.g., received heat load, status of protections etc.), the failure probability is computed through equipment fragility models.

2.2. Cost-Effectiveness Analysis & Optimization

After the assessment of the baseline scenario carried out in the FEA, in the second phase of the methodology (see Figure 1) a heuristic cost-effectiveness optimization algorithm is used to solve the safety measure allocation problem under constraints. The aim is to obtain a set of non-dominated solutions of the allocation problem compatible with the budget constraint assigned.

Notably, the allocation problem belongs to the class of knapsack problems, which involve resource allocation under constraints. As problem size increases, the exact algorithm requires exponentially increasing computational resources to identify the optimal solution. Also, in the specific case of safety barriers allocation to prevent fire escalation, the effectiveness of a barrier in reducing the escalation frequency cannot be precisely known in advance without testing all possible combinations, particularly when multiple barriers are implemented along the same escalation path. This is because the effectiveness of a combination of safety barriers is not merely the sum or a linear combination of the effectiveness of the safety barriers alone, due to the operators used in the specific ETA involved in the safety barriers assessment. Indeed, as well as the effect of safety barriers in terms of PFD and η, their influence on the physical effect must be considered in the vessel fragility gate (e.g. reduced heat load or time to failure of passive fire protection). These issues further limit the applicability of exact algorithms to solve the allocation problem, involving high computational cost.

Therefore, as frequently happen for this class of problem [39,57,58], the optimality is sacrificed in favour of near-optimal solutions that can be obtained in significantly less computational time, using heuristic methods.

The algorithm is developed based on a means-end analysis approach, that is a well-known problem-solving technique [47]. It involves the partition of a larger problem into smaller, more manageable sub-problems. Each sub-problem is then solved to achieve the overall goal. In the present study, the allocation of safety measures is worked out with an iterative procedure. In each iteration, the safety measure allowing the achievement of the goals of the safety plan with the higher cost-effectiveness is selected to progressively build a new safety plan. The iteration continues until no further safety measures can be added without exceeding the total available safety investment budget, which serves as the termination criterion.

Notably, the developed algorithm belongs to the class of greedy algorithms because, at each iteration step, the locally optimal choice (i.e., the most cost-effective safety measure) is selected. Therefore, the algorithm builds the solution incrementally, aiming to approximate a global optimum by iteratively selecting the best available option at each stage. As a result, the algorithm streamlines the solution of the allocation problem and substantially reduces the computational effort as well, as shown by its application to the illustrative case-study (see Section 3.2.2).

Figure 4 illustrates a detailed presentation of the algorithmic procedure, and the remainder of this section describes each step along with the key parameters and formulas involved.

In step 2.1 of the procedure (see Figure 4), based on the results of the FEA, a portfolio of the potential safety measures that can be used to deal with the possible fire scenarios have to be identified. In step 2.2 (see Figure 4) the portfolio is reduced to the available safety measures, discarding the measures exceeding the available budget. Next, in step 2.3 (see Figure 4) a CEA [30] is performed for each safety measure identified in step 2.2. This requires performing both a cost and an effectiveness analysis.

The CEA requires the assessment of all direct and indirect costs related to the implementation each safety measure considered. Reniers and Van Erp [30] proposed to consider eight cost categories when

Table 3
Cost categories for safety measures. Adapted from [30].

Cost Category	Subcategories
Initiation (C_{ini})	Investigation, selection and design material, training, changing guidelines and informing
Installation (C_{ins})	Production loss, start-up, equipment, installation team
Operation (C_{ope})	Utilities consumption and labor Utilities
Maintenance (C_{mai})	Material, maintenance team, production loss, start-up
Inspection (C_{insp})	Inspection team
Logistic and transport (C_{log})	Transport and loading/unloading of hazardous materials, storage of hazardous materials, drafting control lists, relative documents
Contractor (C_{con})	Contractor selection, training
Other (C_{oth})	Office furniture, insurance, and stationery items

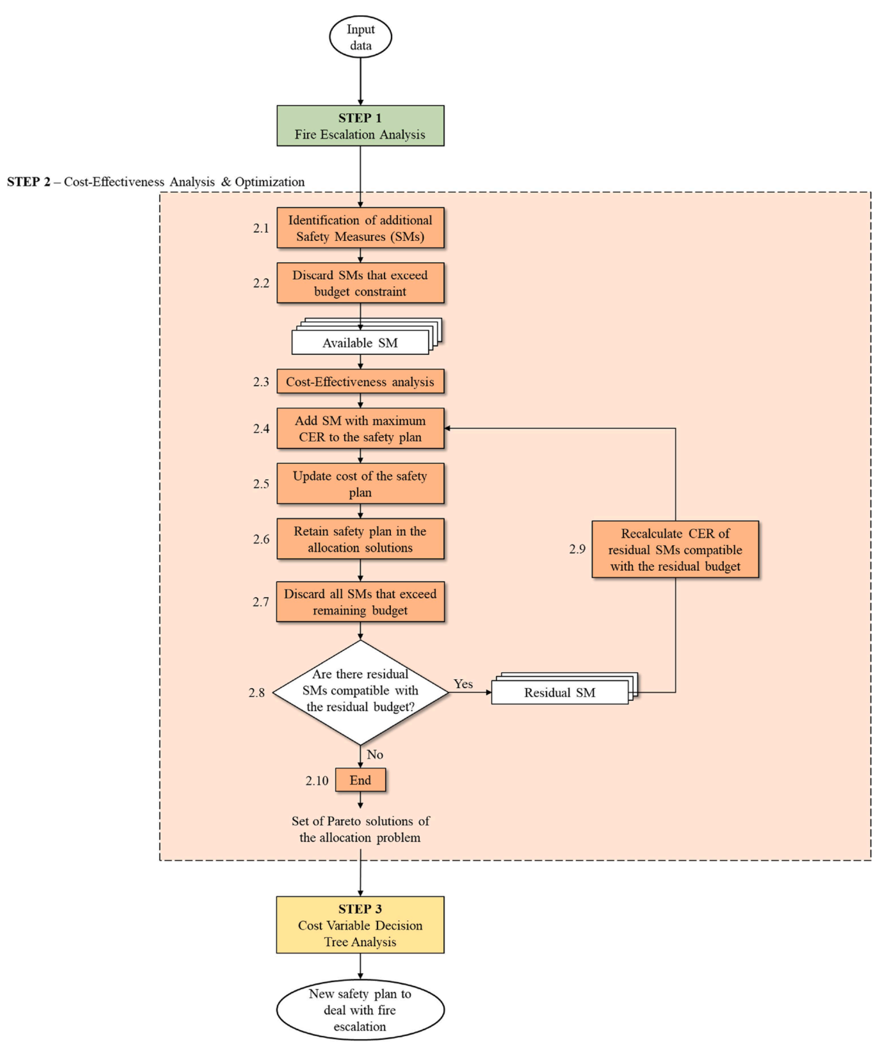

Figure 4. Flow chart of the step 2 of the methodology (SM: Safety Measure; CER: Cost-Effectiveness Ratio).

assessing the cost of safety measures, listed in Table 3. These include investments that occur at the time of measure implementation, such as initial costs and installation costs, as well as costs that occur during the lifetime of the facility. Hence, the present value of costs (C_i) due to the implementation of the *i-th* safety measure is the sum of the initial costs, installation costs, and the discounted present value of all the other recurrent cost items. It can be calculated as follows:

$$C_i = C_{i,\ ini} + C_{i,ins} + \frac{(1+r)^y - 1}{r(1+r)^y}\left(C_{i,ope} + C_{i,mai} + C_{i,insp} + C_{i,log} + C_{i,con} + C_{i,oth}\right) \quad (4)$$

Where i refers to the safety measure, r is the discount rate, y the minimum number of years that the protection measures will operate (time horizon) and the remaining lifespan of the facility [30,42].

In parallel to the cost analysis, the effectiveness analysis is performed involving the assessment of the reduction of fire escalation potential resulting from the implementation of the safety measure. Specifically, the effectiveness is evaluated as a reduction in the overall escalation factor. The procedure to calculate the effectiveness is thus obtained retracing three essential steps of the FEA (see Figure 2). Firstly, it is necessary to update the frequency of all possible primary fires accounting for the presence of the safety measure (i.e., step 1.3), since some types of safety measures may reduce it. Secondly, the ETA needs to be updated considering the safety measure, and the escalation probabilities for target equipment need to be updated due to the presence of the measure (i.e., step 1.5). Finally, an updated overall escalation factor is calculated, E_{new} (i.e., step 1.6), considering the updated values of the primary frequencies and of the escalation probabilities.

In step 2.4 (see Figure 4), the most cost-effective safety measure is added to the safety plan. This requires the calculation of the cost-effectiveness ratio (CER) for each of the safety measures retained in step 2.2:

$$CER_i = \frac{E_0 - E_{new,i}}{C_{TOT} + C_i} \quad (5)$$

Where CER_i is the cost-effectiveness ratio associated to the implementation of the *i-th* safety measure, E_0 is the baseline overall escalation factor (out-put data of the FEA), $E_{new,i}$ is the overall escalation factor updated considering the implementation of the *i-th* safety measure, and C_{TOT} is the total cost of the safety plan, C_i is the cost of the *i-th* safety measure. Clearly, in the first iteration, C_{TOT} is equal to zero as no safety measures has been yet introduced in the safety plan. The safety measure with maximum CER is then added to the safety plan.

In this step, a global check on the effectiveness (i.e., E_0 - $E_{new,i}$) can be introduced to verify whether the safety measure with the highest CER also corresponds to the safety measure that provides the greatest absolute reduction in the escalation factor. In case of discrepancy between the two, both options are retained and evaluated in parallel in the subsequent steps of the methodology. This approach ensures that highly effective but costly safety barriers are not excluded, simply due to their lower CER.

In step 2.5 (see Figure 4) the cost of the safety plant C_{TOT} is updated based on the selected safety measures. Clearly, in the first iteration of the algorithm C_{TOT} will be equal to the cost of the single safety measure introduced in the previous step. In the following iterations, C_{TOT} is calculated taking into account the cost of the safety measures added in the previous iterations:

$$C_{TOT} = C_{TOT,\ old} + C_i \quad (6)$$

Where C_{TOT} is the total cost of the updated safety plan, $C_{TOT,old}$ is the total cost of the safety plan obtained in the previous iteration, and C_i is the cost of the *i-th* safety measure added in the iteration.

In step 2.6 (see Figure 4) the obtained safety plan is retained as a solution of the optimization algorithm, contributing to populate the set of pareto solutions of the allocation problem that will be the output of the second step of the methodology (i.e., the CEAO). Notably, in a bi-objective optimization problem with multiple conflicting objectives (e.g., minimize cost, maximize effectiveness), a solution is Pareto optimal if no other feasible solution exists that improves at least one objective without degrading any other objective. The progressive identification of the pareto solutions is ensured by the criteria adopted in step 2.4 for the selection of safety measures.

In step 2.7 (see Figure 4), the residual budget is calculated (i.e., C_B-C_{TOT}) and the portfolio of residual safety measures is obtained, discarding those exceeding the residual budget.

In step 2.8 the portfolio of residual safety measures compatible with the residual budget is examined. Until one or more residual safety measures are present in the portfolio, step 2.9 in Figure 4 is carried out and steps 2.4 to 2.7 are repeated. In step 2.9 the CER of each residual safety measure identified in step 2.7 is recalculated using Eq. 5. It is worth to remark that the assessment of the overall escalation factors related to the implementation of the *i-th* residual safety measure, $E_{new,i}$, needs to be repeated, in order to consider the simultaneous presence of more than one safety measure. As discussed at the beginning of this section, this ensure avoiding over simplified assumption regarding the effectiveness of safety measures.

The procedure comes to an end (step 2.10 in Figure 4) when in step 2.8 the portfolio of residual safety measures results empty (no residual safety measure to implement, or all residual safety measures exceed the residual budget). The iterative allocation ends, and the set of Pareto solutions of the allocation problem is obtained.

2.3. Cost Variable Decision Tree Analysis

Step 2 of the methodology focuses on optimizing the allocation of safety measures in the most effective way. In step 3 (see Figure 1), the economic convenience of the safety investment is addressed. The aim of this step of the methodology is to determine the economic convenience of investing in a safety plan aimed to prevent fire escalation, considering its cost and the hypothetical benefit deriving from avoided accidents.

To this aim an economic analysis based on a CVDTA was developed [30]. This tool allows to compare two different accident scenarios (i.e., with and without safety investment) and to evaluate which is the more convenient scenario from an economic point of view, taking into account both possible consequences and probabilities.

Unlike conventional ETA used in the risk assessment, CVDT begins with a decision node, followed by a tree of potential consequences for each decision. In addition to probabilities, the cost of each outcome is included, enabling the assessment of the optimal decision. Also, compared to conventional ETA, the structure of the decision tree requires a tailored methodology to identify reference scenarios for each intermediate node (e.g., fire escalation events) and their corresponding final outcomes.

Figure 5 illustrates the main step involved in the CVDTA, and the remainder of this section describe each step in detail. For clarity, Figure 6 reports an illustrative example of the intermediate result from step 3.1, 3.2, and 3.3 of the methodology, to support the description of each step. Specifically, in this study a step-wise approach based on the ETA is proposed to build the structure of the CVDT in step 3.2 of the methodology.

Figure 6a illustrates the decision tree structure developed for escalation scenarios caused by domino effect triggered by fire. The upper branch (continuous line) represents the scenario where the optimal safety plan is implemented (see step 3.1 and step 3.4 for more detail regarding the selection of the safety plan), with the associated costs, frequency and probabilities reflecting the impact of preventive and mitigative safety barriers. The lower branch (dashed line) represents the scenario where no safety investment is made, showing the potential consequences and costs of inaction. As shown in the figure, both the probabilities and costs associated with potential outcomes, as well as the cost of the safety investment, are used to evaluate the total cost of the

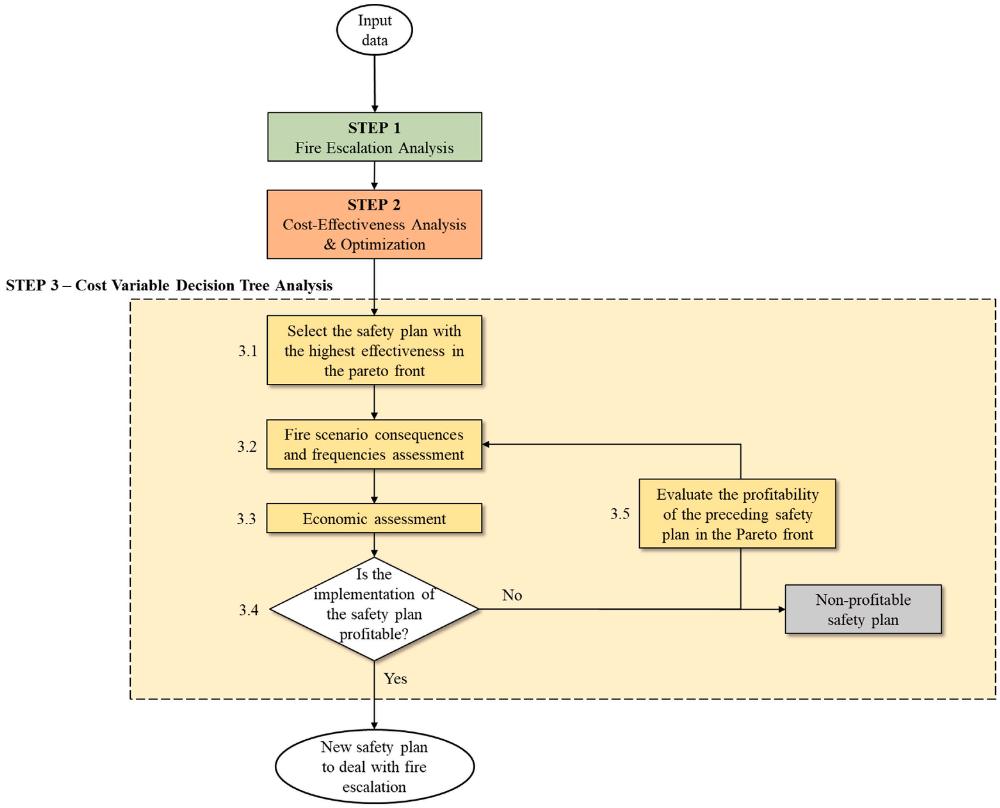

Figure 5. Flow chart of the step 3 of the methodology.

two alternatives. It worth mentioning that the structure of the decision tree can be customized to suit the specific characteristic of a specific site.

In step 3.1 of the procedure (see Figure 5) the safety plan with the highest effectiveness in the set of pareto solution is selected. Then, in order to obtain the CVDT, in step 3.2 the procedure reported in Figure 7 is applied to assess the consequences and the frequencies of the end points of the CVDT. At the end of the procedure, a detailed assessment of the final outcomes in the CVDT, as that shown in Figure 6b, is obtained.

The starting point of the procedure (step a in Figure 7) is the selection of reference primary fire among those identified in the FEA (see Figure 2). The three following steps of the methodology (steps b, c, and d, see Figure 7) have the aim to identify potential target equipment of the primary fire and to calculate the escalation probability for each target. These steps are carried out using the same procedure and tools adopted respectively in steps 1.3, 1.4, and 1.5 of the FEA (see Figure 2), but only considering the reference primary fire scenario selected.

In step e (see Figure 7), the credible combinations of secondary events are then identified. In general, for *n* potential targets affected by a generic primary fire, each of them has 3 possible outcomes (i.e., unmitigated, mitigated, avoided) and the number of possible combinations is 3^n. In step f (see Figure 7), the probability of each credible combination of events is calculated as the intersection of the probabilities of events involved in the combination, considered to be non-disjoint events:

$$P_j = \prod_{i=1}^{n} P_{i,j} \tag{7}$$

Where n is the number of elements of combination *j-th*, and *i* refers to one element of the combination. Table 4, illustrate an example of the calculation procedure in a scenario in which a primary fire may potentially affects 2 target equipment.

The four following steps of the methodology (steps g to j, see Figure 7) have the purpose to cluster the similar outcomes in term of escalation and to assess the overall consequences and vulnerability. Depending on the effect of the safety barriers implemented, the secondary events triggered by a primary fire can be unmitigated, mitigated or avoided, as shown in Figure 8a. However, to outline the CVDT it is necessary to group the possible outcomes in events that may or may not lead to further escalation (Figure 8b). Thus, in step g (see Figure 7) the escalation vectors of combined events are identified and assessed. Also in this case, the physical effect is assessed using conventional literature models [51]. In step h (see Figure 7) the combined events that may lead to escalation are identified using the escalation threshold criteria proposed by Cozzani et al. [53] (see Table S5 of the Supplementary Material). In step i (see Figure 7) the combined events that may lead to escalation are grouped separately. Notably, the probability of each branch of the decision tree (i.e., fire escalation and mitigated scenario) is calculated considering the event of each group as disjoint event (see left side of Table 4) .In step j (see Figure 7), in order to reduce the computational effort, the most probable combined event of each of the two groups (i.e., the fire escalation scenarios and the mitigated scenario) is selected as a reference scenario, leading to the identification of the end point of the decision tree (i.e., Mitigated scenario 1 and Fire escalation, see Figure 8b).

In step k (see Figure 7) the assessment of the upper level of the escalation requires the repetition of the methodology and the fire escalation reference scenario identified in the previous step is used as the starting point.

In step l (see Figure 7), the consequences of the domino accident scenarios are calculated by the approach proposed by Antonioni et al. [59]. Finaly, in step m (see Figure 7), the CVDT is obtained.

After completing the procedure reported in Figure 7, that fulfils the requirements of step 3.2 of the overall methodology (see Figure 5), a CVDT is thus obtained. In the following step (step 3.3 in Figure 5) accident cost are evaluated for all the alternative end point events identified in the CVDT. The accident cost of each node of the tree is calculated using the probabilities and accident costs of the two branches

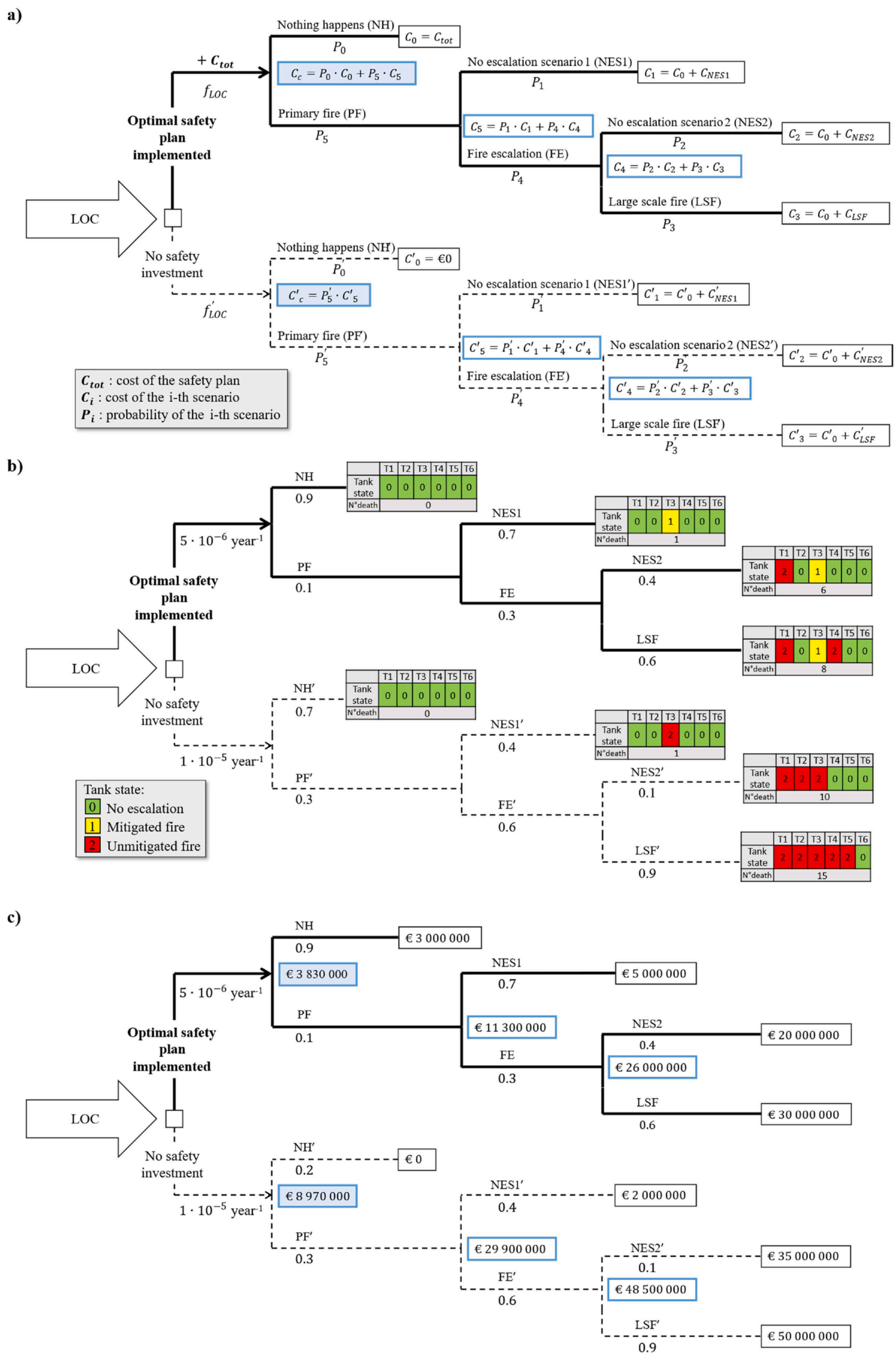

Figure 6. a) Structure of the CVDT adopted in this study. b) Example of a CVDT including the results of fire scenario consequence and frequency assessment (step 3.2 of the methodology in Figure 5). c) Example of a CVDT rolled back to show the total cost of two alternative strategies in fire escalation prevention (step 3.3 of the methodology in Figure 5). CVDT: Cost Variable decision Tree; NES: No Escalation Scenario; FE: Fire escalation; LSF: Large Scale Fire.

connected to the node as shown in Figure 6a. The loss assessment method proposed by Reniers and Brijs [60] is used in the present study to assess direct and indirect accident costs. The total accident cost, including insurance premium, is thus estimated considering the ten cost categories listed in Table 5. Refers also to Reniers and Van Erp for more details [30].

Since each branch of the decision tree includes both the total cost of the safety investment and the cost of the corresponding accident scenario, the accident cost of each branch must be discounted to their present value using the same time horizon applied to the safety investment cost.

The result of step 3.3 (see Figure 5) is a tree where the cost of each node is a running total of the costs of each outcome in a given event pathway. Therefore, the CVDT rolled back lets out the total cost of the

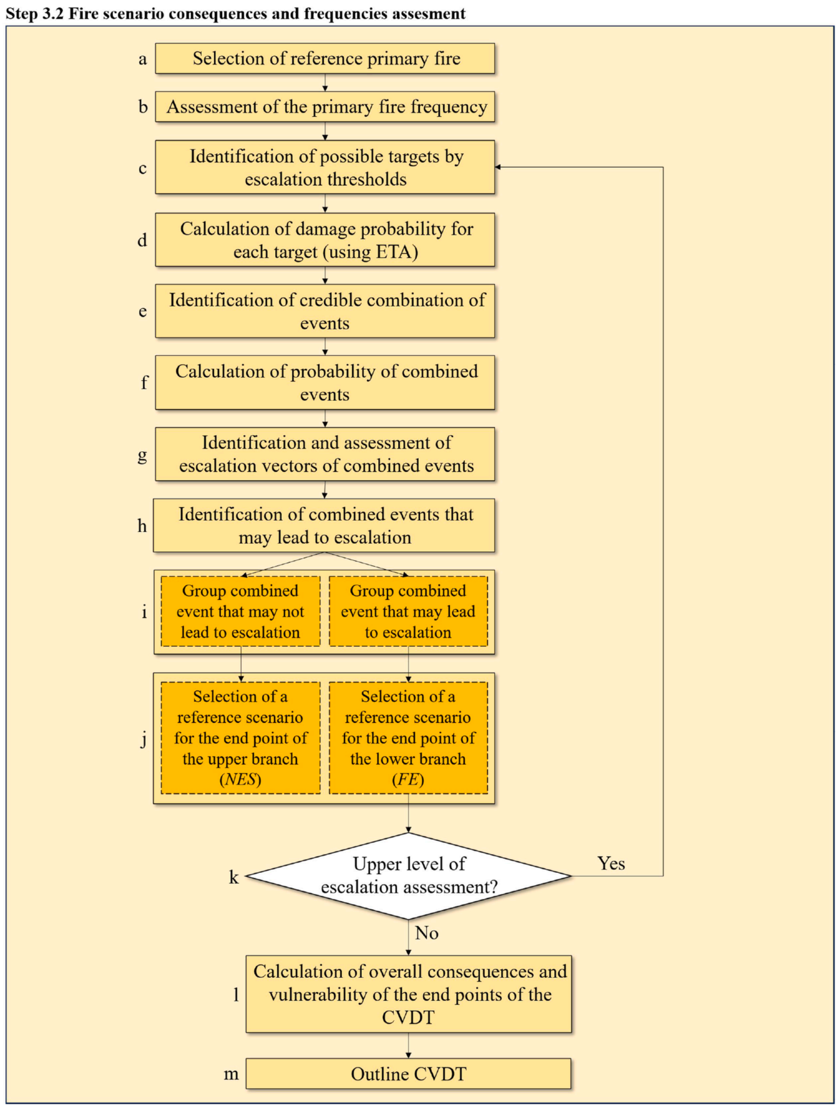

Figure 7. Procedure developed for frequencies and consequences analysis of the decision tree (step 1 of phase 3 of the methodology). ETA: Event Tree Analysis; NES: No Escalation Scenario; FE: Fire Escalation; CVDT: Cost variable Decision Tree.

Table 4
Illustrate an example of the calculation procedure, involved in step e to i of the methodology, for a scenario in which a primary fire may potentially affects 2 target equipment. The escalation potential is defined based on threshold criteria [53].

Combination	Target				Combination Probability	Escalation potential	Decision tree	
	State		Probability					
	T1	T2	T1	T2			Branch	Probability
1	0	0	$P_{1,1}$	$P_{2,1}$	$P_1 = P_{1,1} \cdot P_{2,1}$	False	Escalation	$P_{pf} \cdot \sum_j (P_j \mid Escalation = True)$
2	1	0	$P_{1,2}$	$P_{2,2}$	$P_2 = P_{1,2} \cdot P_{2,2}$	True		
3	0	1	$P_{1,3}$	$P_{2,3}$	$P_3 = P_{1,3} \cdot P_{2,3}$	False		
4	2	0	$P_{1,4}$	$P_{2,4}$	$P_4 = P_{1,4} \cdot P_{2,4}$	True		
5	0	2	$P_{1,5}$	$P_{2,5}$	$P_5 = P_{1,5} \cdot P_{2,5}$	True	Mitigated scenario	$P_{pf} \cdot \sum_j (P_j \mid Escalation = False)$
6	2	1	$P_{1,6}$	$P_{2,6}$	$P_6 = P_{1,6} \cdot P_{2,6}$	True		
7	1	2	$P_{1,7}$	$P_{2,7}$	$P_7 = P_{1,7} \cdot P_{2,7}$	True		
8	1	1	$P_{1,8}$	$P_{2,8}$	$P_8 = P_{1,8} \cdot P_{2,8}$	True		
9	2	2	$P_{1,9}$	$P_{2,9}$	$P_9 = P_{1,9} \cdot P_{2,9}$	True		

two alternative strategies for fire prevention: the hypothetical situation in which the optimal safety plan is implemented and the baseline situation in which the safety investment is not made. Figure 6c reports an example of CVDT after the economic assessment. What stands out from Figure is that if the company decides to carry out the safety investment, it would incur in a total expense of 3M€. However, considering the

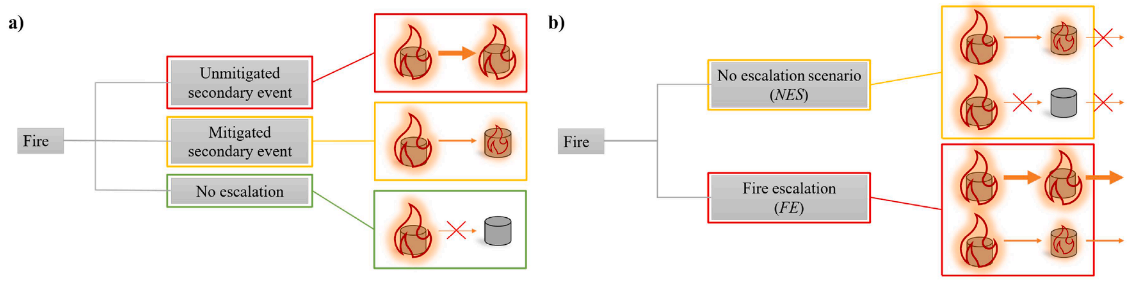

Figure 8. a) Possible outcomes of a primary fire obtained from ETA. b) Clustering of possible outcomes in two groups in order to outline the branches of the decision tree.

Table 5
Accident cost categories. Adapted from [30].

Type of accident cost
Human loss
Medical fee
Property damage
Supply chain loss
Personnel loss
Insurance premium
Intervention fee
Environmental damage
Reputation loss
Legal cost

probabilities and the cost assessed, the overall cost of fire prevention would be 3.83M€, while with no safety investment the cost would be 8.97M€. Therefore, "No safety investment" would result in an expected cost about 2.5 times more expensive than the "optimal safety plan implemented". In addition, the implementation of the optimal safety plan substantially reduces the f_{LOC} of the potential primary fire.

The last step of the methodology (step 3.4 in Figure 5) is a decisional gate. Based on the results of the analysis, decision-makers shall decide whether to implement the optimal safety plan defined. Otherwise, if the CVDTA shows that it is not convenient to implement the optimal safety plan, the profitability of the implementation of the preceding safety plan in in the pareto front shall be assessed, repeating steps 3.2, 3.3, and 3.4 of the procedure reported in Figure 5. Furthermore, even if the CVDTA confirms that the most effective safety plan on the Pareto front is economically justified, decision-makers may consider adopting a less costly alternative plan if the incremental improvement in effectiveness is relatively small compared to the previous plan on the Pareto front.

It is worth mentioning that on the one hand the preceding safety plan in the pareto front is less effective in terms of fire prevention, but on the other hand it is less-expensive in terms of safety investment, thus a different profitability value is obtained by its assessment.

3. Illustrative case-study

3.1. Presentation of the case study

A case-study has been defined and analysed to demonstrate the application of the methodology. A virtual storage plant, shown in Figure 9, has been considered. It consists of five atmospheric tanks containing flammable substances and one pressurized propane tank (T3), each surrounded by a catch basin. The features of the tanks are summarized in Table 6. For the sake of simplicity, no fire safety barriers have been considered in the baseline case. Table 7 reports the safety barriers considered for implementation and the correspondent availability and effectiveness data assumed in the ETA.

The aim of the case-study was not to perform a complete analysis of a real case but rather to demonstrate the application of the proposed

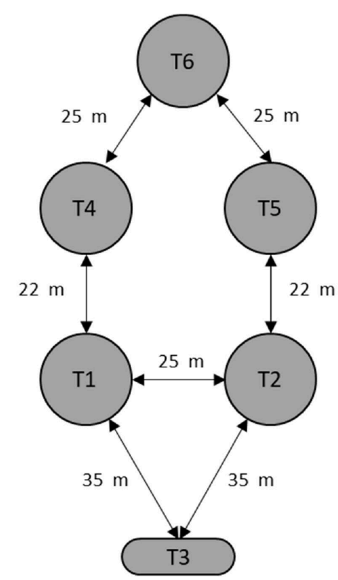

Figure 9. Layout of the virtual storage plant considered in the illustrative case-study.

methodology. Therefore, for the sake of simplicity, a uniform constant population density and a single set of meteorological conditions, which are summarized in Table 8, were considered in the calculations.

The budget assigned for investments in fire protection is assumed to be 3 M€. For the sake of simplicity, only the following accident cost items are considered in the monetarization of accident scenarios:

- In order to assess the damage to humans, a value of statistic life (VSL) of € 5M is assumed [61].
- In order to assess the damage to equipment, the original cost of the equipment and that of the substance contained is considered

Table 6
Data of the equipment items and of the tank inventories considered for the illustrative case study.

Tank name	Type		Diameter (m)	Height (m)	Volume (m^3)	Material	Filling rate	Inventory (ton)	Storage phase
T1	Atmospheric	vertical	24	14.4	6500	Benzene	0.8	4555	Liquid
T2	Atmospheric	vertical	24	14.4	6500	Hexane	0.8	3406	Liquid
T3	Pressurized	horizontal	4	18	250	Propane	0.7	109	Liquid
T4	Atmospheric	vertical	24	14.4	6500	Benzene	0.8	4555	Liquid
T5	Atmospheric	vertical	24	14.4	6500	Hexane	0.8	3406	Liquid
T6	Atmospheric	vertical	24	14.4	6500	Hexane	0.8	3406	Liquid

Table 7
Summary of the data considered in the quantification of the event trees. Data were adapted from Landucci et al. [22]. η: Safety barrier effectiveness; PFD: Probability of failure on demand of a safety barrier.

Safety barrier	Gate	η	PFD
Foam-water sprinkler system	b	0.954	0.002
Fireproofing Coating (10 mm thick)	a	1	0.001
WDS for LPG vessel protection	a	1	0.01

Table 8
Meteorological condition and population density used in the illustrative case-study. T_{amb}: ambient temperature; ρ_{air}: air density; g: gravitational acceleration; RU: relative humidity.

Meteorological conditions					Population density
Wind speed (m/s)	T_{amb} (°C)	ρ_{air} (kg/m^3)	g (m/s^2)	RU	inhabitants/km^2
Negligible	15	1.3	9.81	70.0%	(Uniform)

- In order to assess the cost of clean-up, pipework, equipment installation and restore of auxiliary systems, the cost of damage to equipment is multiplied by 3 [62].

Clearly enough, site-specific values and different assumptions may be introduced in the application of the methodology to a real-life problem.

In addition to the illustrative case study presented in this section, the validation of the algorithm was extended to include three additional case studies, featuring progressively larger numbers of tanks (7, 8, and 9) and significantly more complex allocation problems (up to 262,144 possible allocation combinations in the case study with 9 tanks), as detailed in Section 7 of the Supplementary Material.

3.2. Results of the Case-Study

3.2.1. Fire escalation analysis

In the analysis of the case-study, the fire scenarios arising from the failure of tanks T1-T6 listed in Table 9 were selected as the fire sources. The table also reports the frequencies associated to each fire scenario, derived from the Purple Book [31], considered in the present analysis. As shown in the table, a single stationary fire scenario (Pool or Jet Fire) was assumed as the primary event potentially triggering domino effect in the analysis of the case-study.

Table 9 also reports the list of the equipment items considered as potential targets of the primary fires and the results obtained for the escalation probability in the baseline scenario, calculated by the event tree analysis. It is worth noting that for each primary fire identified, a mitigated secondary event (i.e., target state 1) is not present in the baseline scenario, since no mitigative safety barriers are implemented. As shown in the table, in the baseline scenario all the escalation probabilities are almost equal to 1 due to the absence of safety barriers for fire prevention and limited separation distance among the tanks. The overall escalation factor calculated for the baseline scenario of the case-study considered is equal to $9.11 \cdot 10^{-6}$ $year^{-1}$.

3.2.2. Cost-Effectiveness Analysis and Optimization

Based on the analysis of technical standards, a total of three active and passive safety measures were identified as safety measures to be considered for implementation in order to decrease the probability of fire escalation: fireproofing, water sprinkler system and water deluge system. Table 10 reports a description of the safety systems and the baseline costs assumed for their installation. Clearly enough, site-specific costs shall be adopted in the application of the method to an actual facility.

Figure 10a shows the results of the optimization algorithm used to achieve the most cost-effective solution for fire prevention within the available budget. The dots in the plot represents the 4,092 (corresponding to 2^{12}) possible combinations of the safety measures considered, deriving from the 12 safety measures that may be installed on the 6 tanks considered, and the two alternative allocations of each measure (1 if present, 0 if not present). The orange dots indicate the 63 safety plans selected and tested by the procedure (i.e., from step 2.3 to 2.8 in Figure 4). In the figure, the black point labelled "Baseline" marks the starting point of the allocation process, where no safety measures are implemented. The other black points in the plot represent the safety plan with the maximum cost-effectiveness ratio (CER) selected at each iteration of the algorithm. The final output of the algorithm is the identification of six safety plans (those represented by black dots in the figure), obtained progressively adding the most cost-effective safety measure in each iteration. Table 11 summarize the progressive allocation of safety measures by the allocation algorithm.

The final safety plan has a total cost, C_{TOT}, equal to 2.93M€, and overall escalation factor, E, equal to $2.16 \cdot 10^{-6}$ $year^{-1}$. The escalation probabilities used to calculate the E for the safety plan 6 are reported in Table 9 alongside those for the baseline scenario.

The application of the developed methodology resulted to effectively narrow down the options to be considered, substantially reducing the computational effort. As shown in Figure 10a, the area defined by the orange points is notably smaller than that of the blue points and lies closer to the Pareto front, representing a targeted search area identified by the algorithm. Figure 10b reports the percent decrease of the overall escalation factor (ΔE) in each iteration that is lower when shifting from safety plan 1 to 6. This trend highlights that, as expected, progressing in the iterations, the implementation of additional safety measures is less effective in reducing the E.

A further confirmation of effectiveness of the implementation of the safety plan can be obtained from the comparison of the escalation probabilities. Notably, Figure 11 that compares the escalation probabilities of the primary fires identified before and after the optimal safety plan is implemented. The escalation probability is calculated as proposed by Antonioni et al. [54].

As shown in the Figure, all the probabilities of escalation are decreased at least about of the 30%. However, the primary fire involving tank T3 experiences the highest reduction of the escalation probability (from 1 to 0.32). Since this primary fire has the highest baseline frequency, the safety measures addressing the reduction of the probability of this event received the highest priority.

Table 9
Primary fires considered in the analysis of the case-study, annual frequencies assumed, and results of the ETA for each of the primary fire scenarios considered. Tank state refers to the possible outcomes associated with a generic equipment involved in a domino chain: State 0: no escalation; State 1: mitigated escalation; State 2: unmitigated escalation. LOC: Loss of Containment; $f_{LOC,i}$: frequency of the LOC causing the i-th primary fire; $f_{pf,i}$: frequency of the i-th primary fire. $P^{t}_{esc,i}$: the escalation probability of the i-th primary fire with respect to the t-th target equipment; SP: Safety Plan.

Primary fire					Secondary fire			
Primary fire location	LOC Type	$f_{LOC,\ i}$ (year^{-1})	Type	$f_{PF,\ i}$ (year^{-1})	Target	Target state	$P^{t}_{esc,\ i}$ Baseline scenario	$P^{t}_{esc,\ i}$ SP 6 implemented
T1	G1	5.0E-07	Pool fire	3.25E-07	T2	0	0	0.761
						1	/	0.224
						2	1	0.015
					T4	0	0	0.685
						1	/	0
						2	1	0.315
					T5	0	0.008	0.754
						1	/	0
						2	0.992	0.246
T2	G1	5.0E-07	Pool fire	3.25E-07	T1	0	0	0.680
						1	/	0
						2	1	0.320
					T4	0	0.002	0.729
						1	/	0
						2	0.998	0.271
					T5	0	0	0.672
						1	/	0
						2	1	0.328
T3	G1	5.0E-06	Fire ball	3.50E-07	Escalation unlikely			
	G3	1.0E-04	Jet fire	2.00E-06	T1	0	0.021	0.777
						1	/	0
						2	0.979	0.223
					T2	0	0.021	0.878
						1	/	0.111
						2	0.979	0.011
T4	G1	5.0E-07	Pool fire	3.25E-07	T1	0	0	0.685
						1	/	0
						2	1	0.315
					T2	0	0.008	0.850
						2	/	0.138
							0.992	0.012
					T5	0	0	0.694
						1	/	0
						2	1	0.306
					T6	0	0	0.694
						1	/	0
						2	1	0.306
T5	G1	5.0E-07	Pool fire	3.25E-07	T1	0	0.008	0.754
						1	/	0
						2	0.992	0.246
					T2	0	0	0.745
						1	/	0.240
						2	1	0.015
					T4	0	0	0.694
						1	/	0
						2	1	0.306
					T6	0	0	0.694
						1	/	0
						2	1	0.306
T6	G1	5.0E-07	Pool fire	3.25E-07	T4	0	0	0.685
						1	/	0
						2	1	0.315
					T5	0	0	0.685
						1	/	0
						2	1	0314

3.2.3. Cost Variable Decision Tree Analysis

Safety plan 6, obtained through the progressive addition of safety measures in step 3.2 of the methodology, was identified as the most effective safety plan to consider in the CVDTA. The main results of the analysis are reported in the following. A detailed account of the application of step 3.2 of the methodology (see Figure 5) is reported in Table S8 and S9 Section 6 of the Supplementary Material. For sake of simplicity, the CVDTA focused exclusively on the jet fire from tank T3 since it is the primary fire with the highest frequency of occurrence, as shown in Table 9.

Figure 12a shows the CVDT obtained from the vulnerability analysis carried out for jet fire from tank T3 according to step 3.2 of the methodology (see Figure 5), before the economic assessment is carried out. Thus, the CVDT only reports the consequences of the final outcomes in terms of number of deaths and tank state, as obtained by the vulnerability assessment detailed in the Section 6 of the Supplementary Material. The upper and lower branch of the tree refer respectively to the hypothetical situations in which the optimal safety plan (safety plan 6 in this specific case) is implemented and not (the baseline scenario).

Table 10
Description of the safety measures (SM) considered and the unitary cost assumed for their installation.

Safety mesure	Description	Unitary cost
Water Sprinkler System (WSS)	The water sprinkler system can be installed on atmospheric tanks to protect equipment from external fires.	75 €/ m^2 [63].
Water Deluge System (WDS)	Water deluge system can be installed on pressurized vessels to cool target vessels exposed to external fire.	20,000 €/item [63].
Fireproofing coating (FC)	Fireproofing coating (10 mm thick) can be installed both on pressurized and atmospheric tanks to reduce the wall temperature.	240 €/m^2 [61].

As evident from Figure 12a, the implementation of the optimal safety plan leads to a substantial reduction of the probability to have a large-scale fire derived from the primary fire. Moreover, comparing the two portions of the tree, it is evident that implementing the safety plan also has a relevant impact on the consequences of the possible final outcomes.

Figure 12b shows the CVDT after the economic assessment of the potential benefits deriving from the implementation of the safety plan. As shown in the figure, if the company decides to invest in safety by implementing the optimal safety plan obtained with the optimization algorithm, an overall cost of € 2.93M is foreseen. However, the overall cost of the implementation of the safety plan would be € 7.22M considering the cost of residual accidents as well.

With no safety investment, the expected cost of accidents is of € 25.85M. Therefore, the expected cost of "No safety investment" is more than 3 times higher than the expected cost of "optimal safety plan implementation".

4. Discussion

The reduction of the uncertainty in the process of safety decision-making has a great impact on a company's profitability in the long term. In this perspective, the developed methodology proposes a comprehensive approach to guide a decision maker in the techno-economic analysis of fire prevention safety measures.

The cost-effective optimization model adopted is used to obtain an objective and effective allocation of a limited budget in terms of safety barriers. The effect of adding safety measures is evaluated as the

Table 11
Allocation of the safety measure obtained with the optimization algorithm. Each entry indicates the range of safety plans in which a given safety measure is implemented (e.g., SP1-6: safety measure implemented in the safety plan 1,2,3,4,5, and 6). A slash ("/") denotes that the measure is not applied to the corresponding tank.

Safety barrier	Tank					
	T1	T2	T3	T4	T5	T6
Water sprinkler system	/	SP6		/	/	/
Fireproofing Coating (10 mm thick)	SP2-6	SP4-6	/	SP1-6	SP3-6	SP5-6
WDS for LPG vessel protection			/			

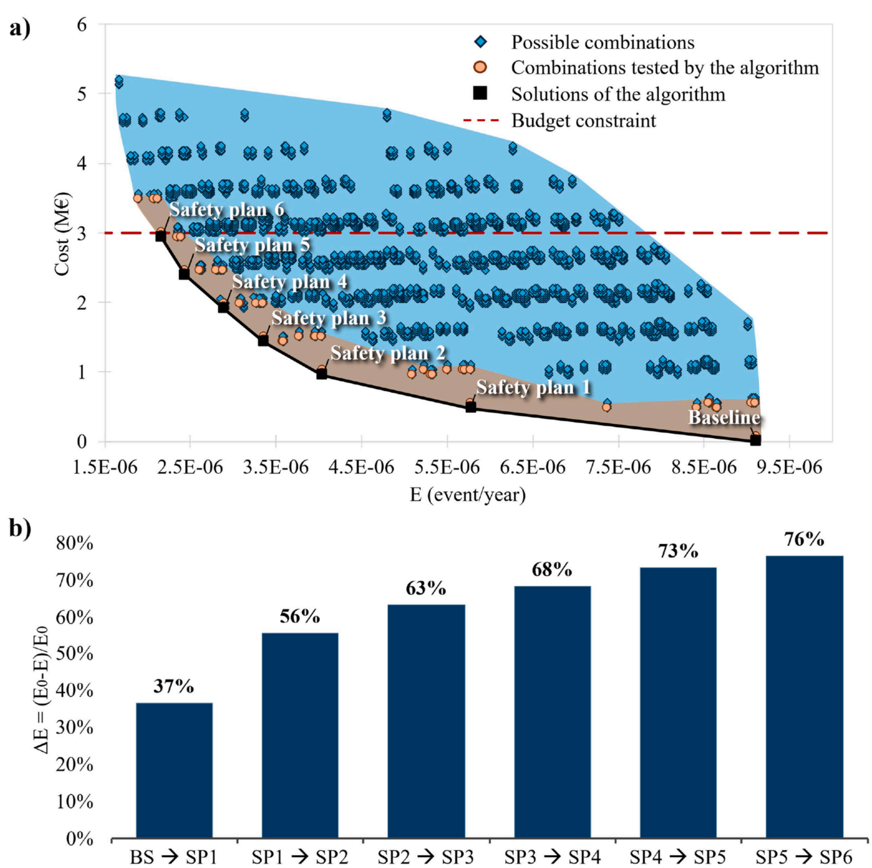

Figure 10. a) Results of the optimization algorithm compared with the entire set of possible combinations of safety measures. The dots in the plot (4,092 points) represents all the possible combinations of the safety measures considered. The orange points indicate the 63 safety plans selectively tested by the algorithm. The black points represent the safety plans with the maximum cost-effectiveness ratio (CER) selected at each iteration of the algorithm. b) Contribution to the reduction of the overall escalation factor (ΔE, %) obtained by the implementation of the specific safety plan considered in each iteration. BS: Baseline Scenario; SP: Safety Plan; E: Overall escalation factor; E_0: Overall escalation factor of the baseline scenario.

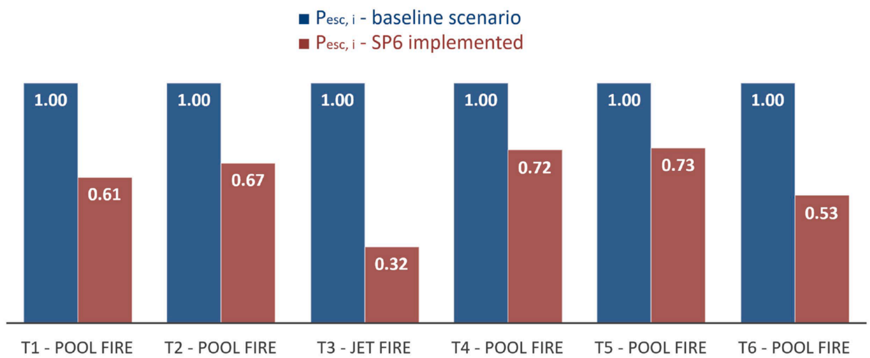

Figure 11. Comparison of the probability of escalation of each primary fire ($P_{esc,i}$) in the baseline scenario and after the implementation of the optimal safety plan (SP6).

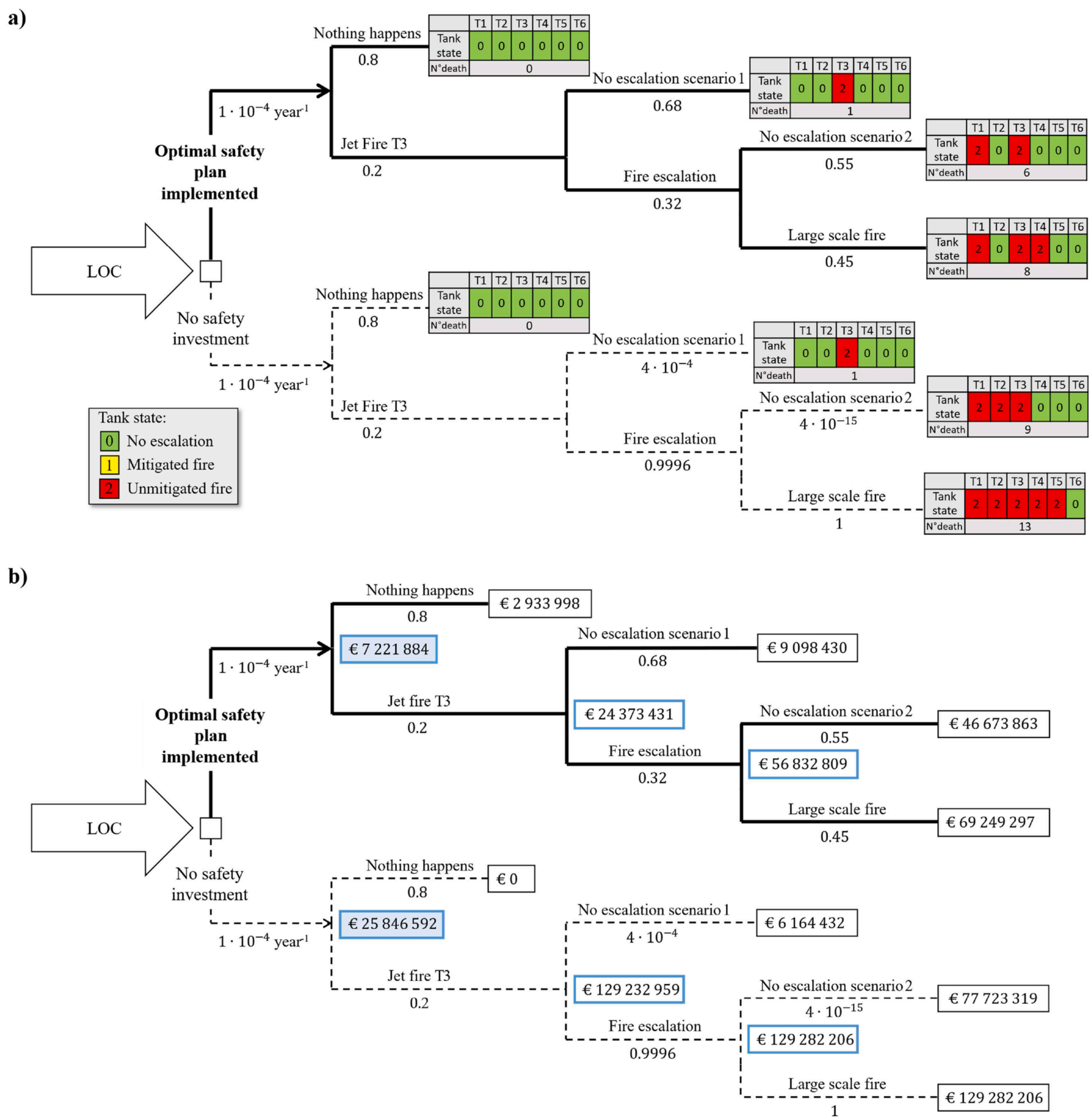

Figure 12. CVDT obtained considering a jet fire from tank T3 as the primary event. a) CVDT before the economic assessment of the final outcomes. b) CVDT including the assessment of the expected costs.

reduction of the overall escalation factor of the area of interest (effectiveness parameters). The allocation algorithm is based on a means-end analysis problem-solving technique to reduce computational cost and to account for the non-additive effectiveness of multiple safety barriers allocation arising from the nonlinear structure of the specific ETA used for the safety barriers assessment. Specifically, the developed heuristic algorithm belongs to the class of greedy algorithms.

Although, greedy algorithm generally does not guarantee the optimal solution for conventional 0/1 knapsack problem, in all the scenarios analysed, the algorithm is shown to effectively reduce the solution space from the complete set of combinations to a smaller, targeted subset, and further to identify a sequence of the most cost-effective plans, thus ensuring the identification of the optimal safety plan.

This is because, the effectiveness function used in the safety barrier allocation problem, defined as the overall reduction of the escalation factor within the facility, exhibits a monotonic increasing behavior (i.e., adding barriers never increases E) and submodularity (i.e., the marginal effectiveness of adding a specific barrier decreases as more barriers were already implemented). This submodularity arises from the fact that the marginal effectiveness of each barrier decreases with the number of existing barriers already active along the same escalation path, due to the multiplicative structure of probabilities in the Event Tree Analysis (ETA). This property supports the use of a greedy algorithm, which is known in the literature to yield near-optimal solutions in maximization problems involving submodular functions [64].

Moreover, in cases where the unit cost of safety measures is significantly lower than the available investment budget, the greedy approach can perform a large number of decision steps. This allows for greater granularity in the allocation process. As established in the literature, under these conditions the greedy algorithm progressively approaches the optimal value, reducing the theoretical gap from the exact solution [64]. Consequently, the maximum relative error becomes increasingly small as the cost of individual barriers decreases and the available budget increases. Thus, especially in large-scale allocation problems where brute-force methods to identify the optimal solution are computationally infeasible, the developed approach proves to be both applicable and effective, as showed in the scenarios analyzed in the illustrative case study and in Section 7 of the supplementary material.

To complement the CEA, not allowing the evaluation of hypothetical benefits deriving from avoided accidents, the CVDTA is proposed as an additional analysis to assess the economic convenience of the implementation of the optimal safety plan, starting from the most effective in the set of Pareto-optimal solutions. To this aim, a novel methodology for the CVDTA was developed, taking into account the possible cascading effects triggered by a fire accident. The case-study evidences the effectiveness of the proposed methodology in showing to the decision makers the preventive and mitigating effects of the safety investment in the domino accident pathway.

In the developed methodology, a bi-objective optimization approach was adopted to simultaneously minimize both the cost of safety measures and the escalation factor (E). As a result, at the end of step 2 of the methodology a set of Pareto-optimal solutions of the allocation problem is obtained. Although the use of a single-objective optimization approach (e.g., minimizing expected loss or maximizing a cost-effectiveness ratio) would be more straightforward compared to bi-objective formulation, it may oversimplify the complex trade-offs involved. Actually, in scenarios where low-probability, high-consequence events are present, plans with significant higher cost may yield in marginal benefits. For example, in the case study presented in Section 3, while a single-objective approach may favour Plan 6 due to its lower fire escalation potential (E), it disregards the steep cost increase compared to earlier plans. As shown in Figure 6b, incremental improvements in effectiveness diminish beyond Plan 4, despite significant additional investment. The decreasing return, that would be obscured in an aggregated single-objective approach, is actually essential for decision makers to recognize, particularly in Step 3.4 of the methodology, where choosing a less costly but slightly less effective plan may be appropriate. Therefore, the use of a heuristic algorithm is essential, as it does not only search for the optimal allocation but also provides intermediate, sub-optimal solutions. As a result, it preserves flexibility in Step 3.4 of the methodology and enables stakeholders to select safety plans that represent an acceptable trade-off between effectiveness and economic feasibility.

Although the current methodology is designed to account only for escalation caused by thermal radiation, the overall framework can be adapted to assess the vulnerability of more complex domino accidents. Notably, in perspective, the calculation approach adopted can be extended to additional escalation scenarios, such as those triggered by blast waves and missiles. Further development may also focus on integrating the dynamic features of fires in the consequence assessment within the CVDTA. However, this would require tailored enhancements to the methodology, potentially requiring to specific probabilistic model as Dynamic Event Tree Analysis or Dynamic Bayesian Network for accident sequence analysis (e.g., [2,65]).

Similarly to other approaches in safety economics that evaluate hypothetical benefits resulting from safety investments [66], a limitation of the proposed methodology concerns the time and effort required to collect the necessary input data, especially for the economic analysis. Accurate estimation of economic consequences relies on detailed, context-specific information, which can be both time-consuming and difficult to obtain, potentially limiting the practicality of the method. However, the evaluation of hypothetical benefits deriving from avoided accidents provides a direct and tangible representation of the value generated by safety investments, thereby enhancing the relevance and interpretability of the results.

5. Conclusions

A novel methodology was developed to support and optimize the decision-making process for fire prevention. A cost-effectiveness optimization model and a CVDTA were combined for a more comprehensive support to the decision-making process. The methodology is able to assess the economics of safety plan implementation, considering both the costs of safety measures and the hypothetical benefits deriving from avoided accidents. The results of an illustrative case-study confirmed the value of the methodology in supporting decision making under budget constraints, addressing safety barrier allocation. The combined approach developed proved to provide a comprehensive support to safety investment decisions when a choice has to be made taking into consideration short-term real costs of safety investment and long-term hypothetical benefits related to avoided accidents. The methodology proposed can easily be tailored adopting different cost-effective optimization models for the safety barriers allocation or developing different decision tree structures to suit site-specific features. Therefore, the novel approach developed represents a further step towards the optimization of safety investments aimed at an effective management of the risk of fire induced domino effects.

Author statement

This is a letter stating that all authors of this manuscript agree with the revised version of the manuscript, and that is can be submitted to RESS.

CRediT authorship contribution statement

Matteo Valente: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Genserik Reniers:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Valerio Cozzani:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ress.2025.111646.

Data availability

No data was used for the research described in the article.

References

[1] Khan F, Cozzani V, Reniers G. Domino Effect: Its Prediction and Prevention, 5. Elsevier; 2021.
[2] Khakzad N. Application of dynamic Bayesian network to risk analysis of domino effects in chemical infrastructures. Reliab Eng Syst Saf 2015;138:263–72. https://doi.org/10.1016/j.ress.2015.02.007.
[3] Ding L, Khan F, Ji J. A novel approach for domino effects modeling and risk analysis based on synergistic effect and accident evidence. Reliab Eng Syst Saf 2020;203:107109. https://doi.org/10.1016/j.ress.2020.107109.
[4] European Parliament and Council of the European Union. Directive, 2012/18/EU on the control of major-accident hazards involving dangerous substances. 2012.
[5] Abdolhamidzadeh B, Abbasi T, Rashtchian D, Abbasi SA. Domino effect in process-industry accidents - An inventory of past events and identification of some patterns. J Loss Prev Process Ind 2011;24:575–93. https://doi.org/10.1016/j.jlp.2010.06.013.
[6] Mannan Sam. Incidents and Loss Statistics. Lees' Loss Prevention in the Process Industries. Elsevier 2012:15–41. https://doi.org/10.1016/B978-0-12-397189-0.00002-1.
[7] Gómez-Mares M, Zárate L, Casal J. Jet fires and the domino effect. Fire Saf J 2008;43:583–8. https://doi.org/10.1016/j.firesaf.2008.01.002.
[8] Yang R, Khan F, Neto ET, Rusli R, Ji J. Could pool fire alone cause a domino effect? Reliab Eng Syst Saf 2020;202:106976. https://doi.org/10.1016/j.ress.2020.106976.
[9] Chen H, Chen G, Xiong C, Wu Y, Li X, Gao X. An inherent safety assessment tool for storage tank farm layout planning based on dynamic propagation modeling simulation of fire domino effects. Reliab Eng Syst Saf 2025;256:110797. https://doi.org/10.1016/j.ress.2024.110797.
[10] Chen C, Reniers G, Zhang L. An innovative methodology for quickly modeling the spatial-temporal evolution of domino accidents triggered by fire. J Loss Prev Process Ind 2018;54:312–24. https://doi.org/10.1016/j.jlp.2018.04.012.
[11] Masum Jujuly M, Rahman A, Ahmed S, Khan F. LNG pool fire simulation for domino effect analysis. Reliab Eng Syst Saf 2015;143:19–29. https://doi.org/10.1016/j.ress.2015.02.010.
[12] Ding L, Khan F, Abbassi R, Ji J. FSEM: An approach to model contribution of synergistic effect of fires for domino effects. Reliab Eng Syst Saf 2019;189:271–8. https://doi.org/10.1016/j.ress.2019.04.041.
[13] MdT Amin, Scarponi GE, Cozzani V, Khan F. Improved pool fire-initiated domino effect assessment in atmospheric tank farms using structural response. Reliab Eng Syst Saf 2024;242:109751. https://doi.org/10.1016/j.ress.2023.109751.
[14] Tamascelli N, Scarponi GE, Amin MT, Sajid Z, Paltrinieri N, Khan F, et al. A neural network approach to predict the time-to-failure of atmospheric tanks exposed to external fire. Reliab Eng Syst Saf 2024;245:109974. https://doi.org/10.1016/j.ress.2024.109974.
[15] Duijm NJ. Safety-barrier diagrams as a safety management tool. Reliab Eng Syst Saf 2009;94:332–41. https://doi.org/10.1016/j.ress.2008.03.031.
[16] DIMAIO F, SCAPINELLO O, ZIO E, CIARAPICA C, CINCOTTA S, CRIVELLARI A, et al. Accounting for Safety Barriers Degradation in the Risk Assessment of Oil and Gas Systems by Multistate Bayesian Networks. Reliab Eng Syst Saf 2021;216:107943. https://doi.org/10.1016/j.ress.2021.107943.
[17] Spoelstra M, Mahesh S, Kooi E, Heezen P. Domino effects at LPG and propane storage sites in the Netherlands. Reliab Eng Syst Saf 2015;143:85–90. https://doi.org/10.1016/j.ress.2015.06.018.
[18] Safety Center for Chemical Process. Guidelines for Initiating Events and Independent Protection Layers in Layer of Protection Analysis, 84. Wiley; 2015. https://doi.org/10.1002/9781118948743.
[19] Pasman HJ, Knegtering B, Rogers WJ. A holistic approach to control process safety risks: Possible ways forward. Reliab Eng Syst Saf 2013;117:21–9. https://doi.org/10.1016/j.ress.2013.03.010.
[20] Mannan Sam. Lees' Process Safety Essentials. Elsevier; 2014. https://doi.org/10.1016/C2009-0-20231-5.
[21] Landucci G, Argenti F, Spadoni G, Cozzani V. Domino effect frequency assessment: The role of safety barriers. J Loss Prev Process Ind 2016;44:706–17. https://doi.org/10.1016/j.jlp.2016.03.006.
[22] Landucci G, Argenti F, Tugnoli A, Cozzani V. Quantitative assessment of safety barrier performance in the prevention of domino scenarios triggered by fire. Reliab Eng Syst Saf 2015;143:30–43. https://doi.org/10.1016/j.ress.2015.03.023.
[23] Mancuso A, Compare M, Salo A, Zio E. Portfolio optimization of safety measures for the prevention of time-dependent accident scenarios. Reliab Eng Syst Saf 2019;190:106500. https://doi.org/10.1016/j.ress.2019.106500.
[24] Mancuso A, Compare M, Salo A, Zio E. Portfolio optimization of safety measures for reducing risks in nuclear systems. Reliab Eng Syst Saf 2017;167:20–9. https://doi.org/10.1016/j.ress.2017.05.005.
[25] Guo X, Ding L, Ji J, Cozzani V. A cost-effective optimization model of safety investment allocation for risk reduction of domino effects. Reliab Eng Syst Saf 2022;225:108584. https://doi.org/10.1016/j.ress.2022.108584.
[26] Ovidi F, Zhang L, Landucci G, Reniers G. Agent-based model and simulation of mitigated domino scenarios in chemical tank farms. Reliab Eng Syst Saf 2021;209:107476. https://doi.org/10.1016/j.ress.2021.107476.
[27] Meyer T, Reniers G. Engineering Risk Management. De Gruyter; 2022. https://doi.org/10.1515/9783110665338.
[28] Yuan S, Chen C, Yang M, Reniers G. Methods for domino effect risk management decision-making, 2021, p. 461-94. https://doi.org/10.1016/bs.mcps.2021.05.014.
[29] Gavious A, Mizrahi S, Shani Y, Minchuk Y. The costs of industrial accidents for the organization: Developing methods and tools for evaluation and cost-benefit analysis of investment in safety. J Loss Prev Process Ind 2009;22:434–8. https://doi.org/10.1016/j.jlp.2009.02.008.
[30] Reniers GLL, Van Erp HRN. Operational Safety Economics 2016. https://doi.org/10.1002/9781118871546.
[31] Boardman AE, Greenberg DH, Vining AR, Weimer DL. Cost-Benefit Analysis. Cambridge University Press; 2018. https://doi.org/10.1017/9781108235594.
[32] Rahman MS, Colbourne B, Khan F. Risk-Based Cost Benefit Analysis of Offshore Resource Centre to Support Remote Offshore Operations in Harsh Environment. Reliab Eng Syst Saf 2021;207:107340. https://doi.org/10.1016/j.ress.2020.107340.
[33] Van Coile R, Lucherini A, Chaudhary RK, Ni S, Unobe D, Gernay T. Cost-benefit analysis in fire safety engineering: State-of-the-art and reference methodology. Saf Sci 2023;168:106326. https://doi.org/10.1016/j.ssci.2023.106326.
[34] Necci A, Cozzani V, Spadoni G, Khan F. Assessment of domino effect: State of the art and research Needs. Reliab Eng Syst Saf 2015;143:3–18. https://doi.org/10.1016/j.ress.2015.05.017.
[35] Landucci G, Cozzani V. Assessment of safety barriers and mitigation of domino scenarios. Dynamic Risk Assessment and Management of Domino Effects and Cascading Events in the Process Industry 2021:249–70. https://doi.org/10.1016/B978-0-08-102838-4.00011-0.
[36] Chen C, Reniers G, Khakzad N. Integrating safety and security resources to protect chemical industrial parks from man-made domino effects: A dynamic graph approach. Reliab Eng Syst Saf 2019;191:106470. https://doi.org/10.1016/j.ress.2019.04.023.
[37] Khakzad N, Khan F, Amyotte P, Cozzani V. Risk Management of Domino Effects Considering Dynamic Consequence Analysis. Risk Analysis 2014;34:1128–38. https://doi.org/10.1111/risa.12158.
[38] Cozzani V, Tugnoli A, Salzano E. The development of an inherent safety approach to the prevention of domino accidents. Accid Anal Prev 2009;41:1216–27. https://doi.org/10.1016/j.aap.2008.06.002.
[39] Janssens J, Talarico L, Reniers G, Sörensen K. A decision model to allocate protective safety barriers and mitigate domino effects. Reliab Eng Syst Saf 2015;143:44–52. https://doi.org/10.1016/j.ress.2015.05.022.
[40] Reniers GLL, Sörensen K. An Approach for Optimal Allocation of Safety Resources: Using the Knapsack Problem to Take Aggregated Cost-Efficient Preventive Measures. Risk Analysis 2013;33:2056–67. https://doi.org/10.1111/risa.12036.
[41] Khakzad N, Landucci G, Cozzani V, Reniers G, Pasman H. Cost-effective fire protection of chemical plants against domino effects. Reliab Eng Syst Saf 2018;169:412–21. https://doi.org/10.1016/j.ress.2017.09.007.
[42] Chen C, Reniers G, Khakzad N. Cost-benefit management of intentional domino effects in chemical industrial areas. Process Safety and Environmental Protection 2020;134:392–405. https://doi.org/10.1016/j.psep.2019.10.007.
[43] Riegg Cellini S, Edwin Kee J. Cost-Effectiveness and Cost-Benefit Analysis. Handbook of Practical Program Evaluation. Wiley; 2015. p. 636–72. https://doi.org/10.1002/9781119171386.ch24.
[44] Dey PK. Project risk management using multiple criteria decision-making technique and decision tree analysis: a case study of Indian oil refinery. Production Planning & Control 2012;23:903–21. https://doi.org/10.1080/09537287.2011.586379.
[45] Mistikoglu G, Gerek IH, Erdis E, Mumtaz Usmen PE, Cakan H, Kazan EE. Decision tree analysis of construction fall accidents involving roofers. Expert Syst Appl 2015;42:2256–63. https://doi.org/10.1016/j.eswa.2014.10.009.
[46] Muennig P, Bounthavong M. Cost-Effectiveness Analysis in Health: A Practical Approach. 3rd ed. John Wiley & Sons; 2016.
[47] Simon HA. The Sciences of the Artificial. Third edition. The MIT Press; 1996.
[48] DELVOSALLE C, FIEVEZ C, PIPART A, DEBRAY B. ARAMIS project: A comprehensive methodology for the identification of reference accident scenarios in process industries. J Hazard Mater 2006;130:200–19. https://doi.org/10.1016/j.jhazmat.2005.07.005.
[49] Jagadeeswaran I, Sriram H. EU 1272/2008 - Classification, Labelling and Packaging of Substances and Mixtures. Medical Device Guidelines and Regulations Handbook. Cham: Springer International Publishing; 2022. p. 261–95. https://doi.org/10.1007/978-3-030-91855-2_14.
[50] Uijt de Haag PAM, Ale BJM, Post JG. The 'Purple Book.' Loss Prevention and Safety Promotion in the Process Industries. Elsevier; 2001. p. 1429–38. https://doi.org/10.1016/B978-044450699-3/50053-7.
[51] Van Den Bosh CJH, RAPM Weterings. Methods for the calculation of Physical Effects Due to releases of hazardous materials (liquids and gases). The Hague (NL): 2005.
[52] Vílchez JA, Espejo V, Casal J. Generic event trees and probabilities for the release of different types of hazardous materials. J Loss Prev Process Ind 2011;24:281–7. https://doi.org/10.1016/j.jlp.2011.01.005.

[53] Cozzani V, Gubinelli G, Salzano E. Escalation thresholds in the assessment of domino accidental events. J Hazard Mater 2006;129:1–21. https://doi.org/10.1016/j.jhazmat.2005.08.012.
[54] Antonioni G, Spadoni G, Cozzani V. Application of domino effect quantitative risk assessment to an extended industrial area. J Loss Prev Process Ind 2009;22:614–24. https://doi.org/10.1016/j.jlp.2009.02.012.
[55] Landucci G, Necci A, Antonioni G, Argenti F, Cozzani V. Risk assessment of mitigated domino scenarios in process facilities. Reliab Eng Syst Saf 2017;160: 37–53. https://doi.org/10.1016/j.ress.2016.11.023.
[56] Alileche N, Olivier D, Estel L, Cozzani V. Analysis of domino effect in the process industry using the event tree method. Saf Sci 2017;97:10–9. https://doi.org/10.1016/j.ssci.2015.12.028.
[57] Du Y, Sun J, Duan Q, Qi K, Xiao H, Liew KM. Optimal Assignments of Allocating and Scheduling Emergency Resources to Accidents in Chemical Industrial Parks. J Loss Prev Process Ind 2020;65:104148. https://doi.org/10.1016/j.jlp.2020.104148.
[58] Singh P, Pasha J, Moses R, Sobanjo J, Ozguven EE, Dulebenets MA. Development of exact and heuristic optimization methods for safety improvement projects at level crossings under conflicting objectives. Reliab Eng Syst Saf 2022;220:108296. https://doi.org/10.1016/j.ress.2021.108296.
[59] Antonioni G, Cozzani V, Gubinelli G, Spadoni G, Zanelli S. The Estimation of Vulnerability in Domino Accidental Events. Probabilistic Safety Assessment and Management. London: Springer London; 2004. p. 3212–7. https://doi.org/10.1007/978-0-85729-410-4_514.
[60] Reniers G, Brijs T. Major accident management in the process industry: An expert tool called CESMA for intelligent allocation of prevention investments. Process Safety and Environmental Protection 2014;92:779–88. https://doi.org/10.1016/j.psep.2014.02.003.
[61] Paltrinieri N, Bonvicini S, Spadoni G, Cozzani V. Cost-Benefit Analysis of Passive Fire Protections in Road LPG Transportation. Risk Analysis 2012;32:200–19. https://doi.org/10.1111/j.1539-6924.2011.01654.x.
[62] Gavious A, Mizrahi S, Shani Y, Minchuk Y. The costs of industrial accidents for the organization: Developing methods and tools for evaluation and cost-benefit analysis of investment in safety. J Loss Prev Process Ind 2009;22:434–8. https://doi.org/10.1016/j.jlp.2009.02.008.
[63] Estimate Florida Consulting (EFC). How Much Does a Commercial Fire Sprinkler System Cost? n.d. https://estimatorflorida.com/how-much-does-a-commercial-fire-sprinkler-system-cost/ (accessed October 24, 2024).
[64] Nemhauser GL, Wolsey LA, Fisher ML. An analysis of approximations for maximizing submodular set functions—I. Math Program 1978;14:265–94. https://doi.org/10.1007/BF01588971.
[65] Ricci F, Misuri A, Scarponi GE, Cozzani V, Demichela M. Vulnerability Assessment of Industrial Sites to Interface Fires and Wildfires. Reliab Eng Syst Saf 2024;243: 109895. https://doi.org/10.1016/j.ress.2023.109895.
[66] Chen C, Reniers G, Khakzad N, Yang M. Operational safety economics: Foundations, current approaches and paths for future research. Saf Sci 2021;141: 105326. https://doi.org/10.1016/j.ssci.2021.105326.