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Agent-based model and simulation of mitigated domino scenarios in chemical tank farms

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A B S T R A C T

The growing trend of interconnecting two or more chemical process or storage facilities represents a critical safety issue, since an accident can easily escalate from an industrial establishment to the nearby plants resulting in a domino effect. However, common safety analyses often ignore cascading events in chemical tank farms, their complex and transient evolution, and mitigation effects of add-on safety measures. The aim of the present work is to develop a structured approach for the assessment of complex domino events accounting for the influence of safety barriers. The approach is based on the adoption of Agent-based Model and Simulation for the assessment of Domino effect in presence of add-on Protections (DAMS-P). For the first time, the assessment of mitigated cascading events in chemical tank farms is carried out accounting for the transient evolution of multiple scenarios and related synergistic effects, and the effect of safety barriers and their possible time-dependent degradation. A verification of DAMS-P is firstly performed through the comparison against analytic probability evaluation based on event tree analysis and tested through the application of industrial cases. The results obtained constitute a useful support for decision-making and for the identification of critical barriers and their performance evaluation.

1. Introduction

Chemical and process facilities feature relevant hazards associated with the high inventories of dangerous substances, which may lead to the occurrence of large fires, explosions, and contaminations [1]. In fact, severe cascading events may occur when an accidental scenario (namely, the "primary" scenario) propagates to neighbouring process units, causing multiple "secondary" events. The described phenomenon is referred to as domino effect and often occurred in the past decades, leading to an amplification of the consequences, with respect to those of the primary scenario [2–5].

In this framework, the growing trend of interconnecting two or more facilities (i.e., forming a "chemical cluster" or "chemical industrial park" - CIP) represents a more critical issue, since an accident can easily escalate from an industrial establishment to the nearby plants, especially when considering multiple storage units located in chemical tank farms [6]. However, common quantitative safety analyses often ignore cascading events in CIPs and tank farms [7].

Despite the systematic assessment of domino effects is introduced in several legislations [8–10] and standards [11], the quantitative analysis of cascading events and their implementation in systematic quantitative risk assessment (QRA) studies is a complex task. For this purpose, several technical and scientific works were devoted to the development of methods for the quantitative assessment of domino effects, as

Abbreviations: ABMS, Agent-based Model and Simulation; BLEVE, Boiling Liquid Expanding Vapour Explosion; CIP, Chemical Industrial Park; DAMS, Agent-based Model and Simulation for the assessment of Domino effect; DAMS-P, Agent-based Model and Simulation for the assessment of Domino effect in presence of add-on Protections; EEI, External Emergency Intervention; ETA, Event Tree Analysis; FWS, Foam/Water System; LOPA, Layer of protection analysis; PFD, Probability of Failure on Demand; PFP, passive fire protection based on fireproofing coating application; QRA, quantitative risk assessment; SB, Safety Barrier; TTF, Time to Failure; TFM, time for final mitigation; WDS, Water Deluge System.

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documented by Necci et al. [4].

Relevant contributions addressed the implementation of domino effect in the "standard" QRA framework based on the combined estimation of frequency and consequences [1,12]. Multiple tools were developed and applied to carry out the evaluation of domino effect, such as: risk matrix screening [13,14], Monte Carlo simulation [15,16], event tree [17,18], graph theory [19], Bayesian networks [20–24], and other tools interfaced with a geographical information system [25,26].

More recently, domino effect assessment by agent-based modelling and simulation (DAMS) was proposed as an alternative tool to undertake the analysis of multiple scenarios [27,28]. The agent-based modelling and simulation (ABMS) relies on a bottom-up approach that describes a complex system through the interaction between its basic elements, i.e. "agents", including their features [29]. ABMS predicts the behaviour of the overall system by analysing the interactions of agents; thus, from the micro-scale perspective.

ABMS adopts Monte Carlo simulations to obtain probabilistic results. The main advantage over other approaches based on Monte Carlo simulation such as FREEDOM [15] and FREEDOM II [16] is shifting the focus from the domino effect chain (namely, "macro level" analysis) to the behaviours of each single unit (namely, "micro level" rules) [27]. In practice, the failure probabilities and frequencies of each piece of equipment are evaluated directly by the code routine and are not an input to the model. Hence, errors are reduced and a larger number of scenarios can be implemented, since no modification to the model input are required.

The ABMS approach is mainly used for the analysis of social phenomena, such as: manufacturing processes [30], evacuation scenarios [31], software evolution [32], flood preparedness and recovery of manufacturing enterprises [33], human resources management [34], and virus epidemiology [35,36]. Some examples of the application of ABMS in the industrial field are: emergency response and resources allocation [37], flood incident management [38], security management [39], and resources allocation for defence of spatially distributed physical networks [40].

The application of the ABMS approach to the domino events in CIPs resulted in the DAMS tool [28], which copes with multiple simultaneous scenarios, synergistic effects, dynamic time evolution, keeping low computational costs and reliable results. However, the current development of DAMS features relevant limitations that impair its industrial application, due to the limited equipment types and accident scenarios that are implemented. Moreover, prevention and mitigation measures, aimed at respectively reducing the credibility and severity of the potential domino escalation, are not yet implemented in the DAMS.

Nevertheless, it is of utmost importance to consider safety barriers (SBs) in domino effects analysis, in order to derive sound information on the facility response given a primary event and to provide more accurate risk evaluations. Recent literature studies focused on the implementation of SBs in the analysis of cascading events [41–43] and several simplified methodologies were developed, such as:

- Layer of Protection Analysis (LOPA): based on the concept of independent protection layers (IPLs) [44];
- the simplified risk-based approach proposed in the IEC 61508 standard: it evaluates the safety integrity level for safety instrumented systems;
- MIRAS method proposed within the ARAMIS project: extending the LOPA and IEC 61508 standard approaches.

More recently, a two-parameters approach was proposed for the specific framework of domino effect prevention, based on the probability of failure on demand (PFD) and effectiveness of the barrier [45]. The PFD expresses the probability that a SB is unavailable when it is required to perform its safety function, and the effectiveness is the probability that the SB successfully performs its function once successfully activated. The aforementioned approach was implemented in quantitative risk assessment studies and allowed to define specific key performance indicators for the assessment of SBs performance [42]. This approach was adopted to support quantitative studies dealing with mitigated domino scenarios, based on Bayesian networks [46], dynamic Bayesian network [23,24], and graph theory [18], performing also cost-benefit analyses [18,46].

However, these methodologies imply the definition of conditional probabilities, which is difficult to evaluate and likely not reliable for large-scale industrial facilities [22,28]. Despite the reliability of the common methods, domino effect assessments in chemical clusters and complex tank farms require approaches that do not introduce further complexity to the already difficult system. In the literature, there is a lack of tools overcoming the issue of facilitate the modelling of cascading events while preserving the accuracy of results and the possibility to analyse different settings, such as complexity of layouts and the critical implementation of SBs.

The aim of the present work is to develop a structured approach for the assessment of complex cascading events accounting for the influence of SBs adopting an Agent-based Model and Simulation approach [28]. The novel tool is indicated as DAMS-P in the following (where "P" denotes the implementation of protection systems). For the first time, a simplified but rigorous assessment of cascading events in presence of protections in chemical tank farms is carried out. DAMS-P allows to account for the interdependencies between different safety barriers and equipment items. The proposed bottom-up approach overcomes the issues of common methodologies related to the complexity of the scenario evolution and the severe level of detail of the input data required for the analysis.

The rest of the paper is organized as follows: the methodology is presented in Section 2, Section 3 describes the case studies, both considering a simplified case supporting the verification of the tool and the extension to complex layouts. The results are discussed in Section 4, and Section 5 provides some conclusions.

2. Methodology

2.1. Overview

The methodological approach aimed at the development of DAMS-P is summarized in Fig. 1.

The primary elements of a chemical tank farm are the storage units, which can be grouped in two main categories: atmospheric and pressurised equipment items. Therefore, the initial phase of the study (Phase A, see Fig. 1) consists of equipment items schematization in terms of geometry and failure mode; pressurized and atmospheric tanks are both

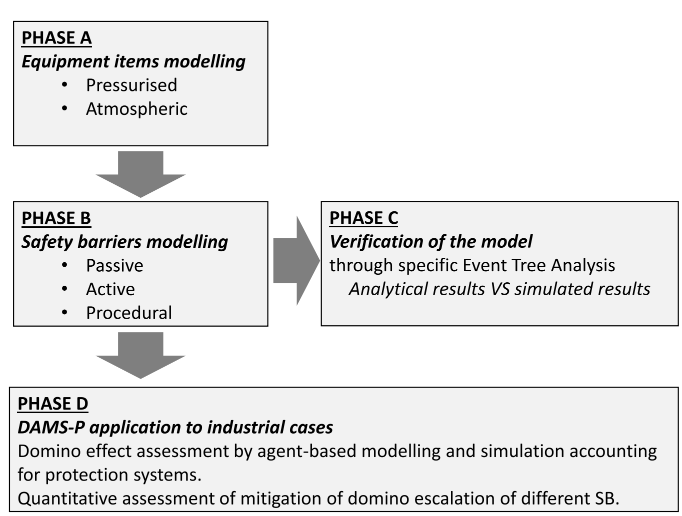

Fig. 1. Methodological approach adopted in the present study.

considered. Pressurized horizontal vessels (such as storage or buffer tanks) are pressure equipment subjected to a maximum allowable pressure greater than 0.5 barg [47]. The considered equipment working at atmospheric pressure are vertical storage tanks, dedicated to the storage of liquids [48].

The second phase of the study (Phase B, see Fig. 1) deals with SBs modelling that represents the core of the present work. Add-on safety barriers are characterized by defining quantitative performance parameters (see Section 2.3). For the sake of exemplification, only systems for the protection against fire are developed in this work. Equations and procedures developed for the equipment modelling are briefly described in Section 2.4, together with the overview of the agent-based approach. Details on the analytical procedures related to the approach can be found in [27,28].

In Phase C (see Fig. 1), the numerical model is verified; a simplified test case is developed, and specific event tree analysis (ETA) is performed for the evaluation of final scenarios conditional probabilities. The analytical results are compared against the numerical results obtained from DAMS-P. After verification, the model is applied for the analysis of a complex chemical storage park and the effect of the different SBs in the mitigation of domino escalation is assessed (Phase D, see Fig. 1).

In order to ease the Reader in the application of the tool, a conceptual scheme is shown in Fig. 2, which schematizes the input (input phase), indications on the calculation procedure (model application), and the possible utilization of the results obtained (output phase). As shown in Fig. 2, the input for the application of DAMS-P is related to the features of the plant under analysis, in particular this information may be derived from a simplified layout, equipment list and process flow diagram (see Step 1.1 in Fig. 2). In this step, the SBs associated with each equipment item are listed and their performance data are assessed; Section 2.3 summarizes the specific characterization procedure for different SBs types. Next, the information about the surrounding environment (Step 1.2 in Fig. 2) is collected to carry out the consequence assessment, i.e. the physical effects estimation for both primary and secondary scenarios associated with each piece of equipment. In the present study, which deals with fired domino effect, heat radiation is the only impact vector, thus a heat radiation matrix is obtained (Step 1.3 in Fig. 2).

The input data are then inserted into the model as "static attributes", i.e. information that is fixed (for instance, the spatial positioning of tanks) and does not update during the simulation. The model application (Step 2 in Fig. 2) concerns two interacting entities: the agent model and the environmental model. The agent model (Step 2.1 in Fig. 2) represents a single piece of equipment, featuring a static and a dynamic part. The static part stores the fixed data, whilst in the dynamic part the item changes its state according to heat load received during the domino scenario (Fig. 4 shows the detailed dynamic agent model). The environment model and the agent model exchange information about the escalation vectors (heat load in Fig. 2) and the states of each piece of equipment (agent state in Fig. 2). The model performs Monte Carlo simulations to obtain probabilistic results (Step 3.1 in Fig. 2). Finally, the raw results can be post-processed to hierarchize different protection configurations (Step 3.2 in Fig. 2) and the obtained risk-based classifications can be employed by several end users, such as those reported in Fig.2 (Step 3.3). A brief discussion on the possible final users of the DASM-P is given Section 4.2.1.

2.2. Equipment modelling

The modelling of pressurized and atmospheric equipment relies on the implementation of the failure mode of the considered vessel. As stated in Section 2.1, domino events triggered by fires are considered in the present work. In this specific case, the probability of equipment damage depends on the time to failure of equipment items exposed to fire, namely, ttf_Q [49]. According to the methodology described in [49], ttf_Q is calculated through correlations as a function of the heat flux received by the equipment (Q) [49]; Eq.s (1) and (2) report the correlation for atmospheric and pressurized vessels, respectively:

$$\ln(ttf_Q) = -1.13\ln(Q) - 2.67{\cdot}10^{-5}{\cdot}V + 9.9 - \ln(60) \tag{1}$$

$$\ln(ttf_Q) = -0.95{\cdot}\ln(Q) + 8.85{\cdot}V^{0.032} - \ln(60) \tag{2}$$

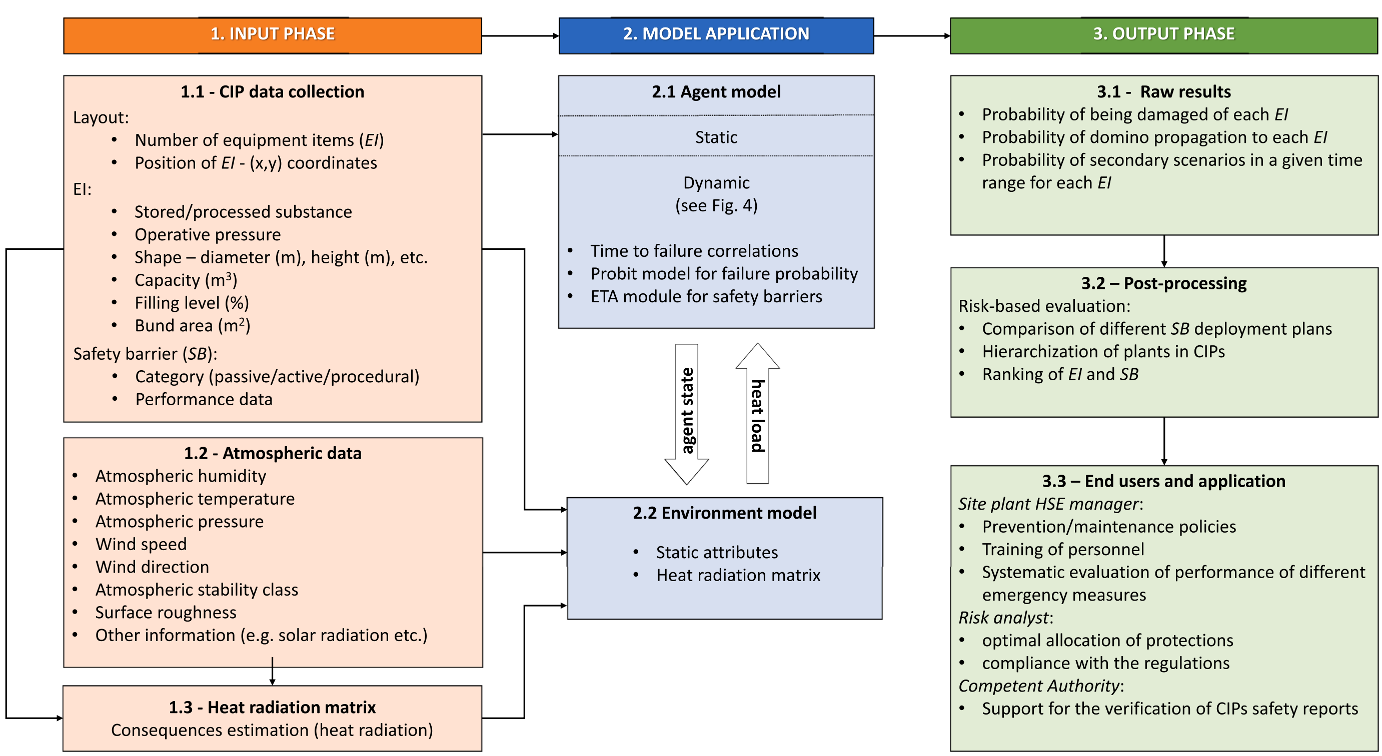

Fig. 2. Schematic procedure for the implementation and application of DAMS-P.

where: ttf_Q is expressed in min; Q is the received heat flux in kW/m^2, and V is the nominal capacity of the vessel, in m^3.

The correlations are implemented in the DAMS-P accounting for the synergistic effect of multiple heat loads received at different times. This is implemented through a mathematical scheme developed in [28]. Hence, the Q term in Eq.s (1) and (2) is an effective value of all the heat fluxes received by the equipment and it is a function of the different heat radiations (Q_r) received from different individual sources (i.e., primary events).

2.3. Safety barriers schematization and modelling

In order to implement the SBs in the DAMS-P, a classification is firstly introduced. According to [45], SBs are classified in four different categories: (i) inherently safer design, (ii) passive protection systems, (iii) active protection systems, and (iv) procedural and/or emergency measures.

Inherently safer design plays a major role in the early stage of process design [50]. It involves actions such as: minimizing the inventory of hazardous materials, selecting safer operational conditions, and modifying the layout with respect to equipment interactions in case of accident. Hence, inherently safer design is not easily applicable in existing plants, and it was not further investigated in the present study.

Therefore, this work focuses on the other three SBs categories, as shown in Fig. 3:

- Passive protection systems: these barriers do not need any activation to achieve their function. They are physically present as permanent features on the equipment. They do not require human action, information sources, or external energy supply to be activated;
- Active protection systems: in this case, an external activation is needed to perform the safety function. In fact, active systems typically need a sequence of detection-diagnosis-action to perform their action. Both automatic systems and/or human actions can carry out the activation sequence;
- Procedural and emergency measure: the safety barrier includes all the internal and external procedures, which can manage and reduce the domino escalation likelihood.

Among SBs, different hardware, software, and procedural systems are available [51]. A summary of the devices for the prevention/mitigation of domino events triggered by fire implemented in the present work is given in Table 1. All the considered SBs need a specific approach to assess whether the SB is actually effective in reducing the domino escalation. The performance assessment of SBs is carried out through a dedicated ETA [52] built for each SB. Each ETA starts from a primary event (e.g., a fire scenario), which affects a target piece of equipment provided with the SB under evaluation. Then, the quantification of SB in the ETA is possible through two performance parameters, namely [41,42]:

- PFD: expressing the capability of each SB to respond on demand;
- Effectiveness (η): representing the probability that the SB, once successfully activated, will be able to effectively prevent/mitigate the escalation.

Table 1
Overview of safety devices implemented in the DAMS-P and quantification of effectiveness and availability of barriers based on baseline literature data [42].

Category of SBs	Gate type (see Fig. 3)	Safety device	Availability (*PFD*)	Effectiveness (*η*)
Passive protection systems	a – single composite probability	Fireproofing	0	0.999
Active protection systems	a – single composite probability	Foam/Water system (FWS)	$5.43 \cdot 10^{-3}$	0.954
		Water deluge system (WDS)	$4.33 \cdot 10^{-2}$	1
Procedural emergency measures	c – discrete probability distribution	External Emergency Intervention (EEI)	$1 \cdot 10^{-1}$	0 / 1

In order to implement the protections in the common ETA methodology, a gate is associated with each SB based on its specific features. In particular, three gates are considered. Fig. 3 describes the gates and summarizes the approach for their quantification; more details on the approach can be found in [42].

In the present study, gate types “a” and “c” are implemented. In particular, gate “a” is associated with passive and active protection systems. The intervention of external emergency teams, representing an example of procedural measure, is evaluated through the gate type “c”. Table 1 summarizes all the values implemented for the performance parameters, for each SB considered in the present study. Whereas, the main features of passive, active and procedural protections are described in Section 2.3.1, 2.3.2, and 2.3.3, respectively.

2.3.1. Passive protection systems

A passive fire protection (PFP) is defined as “barrier, coating or other

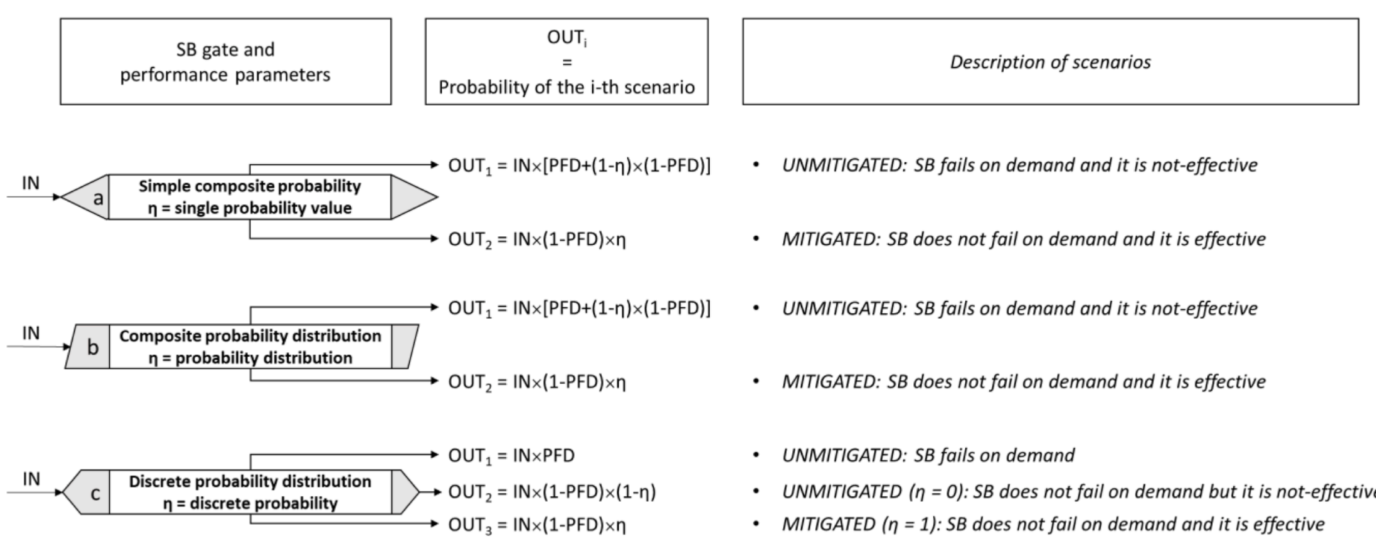

Fig. 3. Definition of gate classes for the safety barriers modelling and associated operators [42]. IN = probability of the upstream event.

safeguard that provides protection against the heat from a fire without additional intervention" [53]. PFP aims at protecting the equipment until the fire is extinguished by other methods (active protections, exhaustion of fuel, etc.). This SB category includes: insulation, secondary-containment structures, drainage, and compartmentalization [54]. The most common measure is fireproofing, i.e. heat resistant coatings applied on the external surface of equipment [52]. Usually, fireproofing is installed together with a pressure safety valve. During the fire exposure, the vessel undergoes relevant pressure build-up induced by the heat up caused by fire [55,56]. The combined effect of fireproofing and pressure safety valve reduces the mechanical and thermal stresses of the exposed steel walls, delaying the vessel failure [57,58].

However, pressure relief itself is not able to prevent the vessel failure [52] and it is not further investigated in this work. Conversely, the fireproofing (hereinafter referred as PFP) limits the equipment walls heat-up and, thus, the loss of strength of materials, proving additional time before the equipment failure. In fact, the key parameter suggested by API standard 2218 [53] to drive the PFP selection is the rated protection time. The evaluation of this parameter is complex, since it involves experimental investigation of the performances of the fireproofing material during fire exposure, as well as the numerical modelling of the eventual degradation [44,59]. These phenomena may be considered introducing the time to failure of the fireproofing, namely ttf_{PFP}. For the sake of simplicity, ttf_{PFP} is estimated according to simplified approach reported in [23]:

$$ttf_{PFP} = 150.0 \cdot k^2{}_{PFP} - 262.98 \cdot k_{PFP} + 115.28 \tag{3}$$

where ttf_{PFP} is in min and k_{PFP} is the thermal conductivity of the PFP material in W/(m K). Since coating materials gradually degrade during the fire exposure, their thermal conductivity increases in time [59]. Therefore, time dependent correlations were developed to reproduce the behaviour of k_{PFP} to be implemented in Eq. (3) [23,41,44]:

$$k_{PFP} = -4.308 \cdot 10^{-7} \cdot t^3 + 4.209 \cdot 10^{-5} \cdot t^2 + 6.720 \cdot 10^{-4} \cdot t + 3.199 \cdot 10^{-1} \tag{4}$$

where t is the time from the start of fire exposure, in min. In order to provide conservative estimations, the maximum additional protection time limited to a maximum of 60 min, according to a previous study [23]. In this work, this lapse of time is estimated as an extension of the expected time to failure of the vessel and the effective time to failure of the vessel (TTF) is evaluated through Eq. (5):

$$TTF = ttf_Q + ttf_{PFP} \tag{5}$$

where ttf_Q is the time to failure of the vessel due to the incoming heat radiation (see Eq.s (1) and (2)).

A null value of PFD was associated with the PFP, i.e., a unitary probability of activation is assumed, being the coating already in place on the equipment at the moment of the fire (thus, without the need of external activation). However, PFP effectiveness may be affected by the degradation and/or the incorrect installation, limiting the barrier effectiveness [60,61]. Hence, a non-unitary value of η was considered [42] (see Table 1).

2.3.2. Active protection systems

Active protection systems usually work by activating three subsystems in chain: i) a detection system (fire/smoke and/or heat detector), ii) a signal processing (logic solver, control panel, etc.) and, iii) an actuation system (mechanical, instruments, human, etc.) [62]. Active barriers for fire protection aim at delivering a firefighting agent (water/foam, usually) either to extinguish the flame or to cool the equipment walls. In this work, both types of active protections are considered and the following main systems are analysed:

- foam/water systems (FWS);
- water deluge systems (WDS).

FWS are activated for local fire extinguishment and are installed on the vessel to protect. Thus, FWS are typically adopted to mitigate tank/pool fires [52] and in this work are considered to be installed only on atmospheric tanks [63]. FWS reduce the flame emissivity power (Q_f), thus the heat load emitted by the flame [64]. If FWS is successfully activated, the heat radiation emitted by the tank/pool fire and received by potential targets (Q_{em}) is estimated through Eq. (6) [18,65].

$$Q_{em} = Q_f \cdot (1 - \alpha \cdot \varphi) \tag{6}$$

where: $\alpha = 60\%$ is an effectiveness parameter and $\varphi = 75\%$ is a radiation reduction factor. The settings for both α and φ were derived from a previous study [18].

WDS act on the target units, delivering water on the protected surface, cooling the walls and slowing their loss of strength. Hence, WDS are aimed at the extension of the equipment time to failure and are typically installed on pressurized vessels [63]. The safety function performance is expressed through the heat radiation reduction factor (ϑ); this enables estimating the effective heat flux received by the equipment item (Q_r) in presence of WDS as follows [41]:

$$Q_r = Q_{em} \cdot \vartheta \tag{7}$$

where Q_{em} is the heat flux received by the target in absence of WDS intervention (thus, received directly from the flame, see Eq. (6)). According to previous studies [41], a value of 0.5 is assumed for ϑ based on a review of available experimental tests carried out on WDS.

2.3.3. Procedural and emergency measures

Procedural and emergency measures include all the company's operating and safety procedures dealing with equipment protection, together with all the external emergency services. The safety action is usually performed by mobilizing resources such as mobile firefighting equipment, water reservoirs, emergency trained personnel, etc. [45,52,62]. Different types of emergency operators may be involved, such as e.g. internal emergency team, external fire brigades, local/national authorities, and neighbouring companies [66]. The present study only considers the external emergency teams' intervention (EEI) as add-on safety measure.

EEI involves the delivery of fire-fighting agents (typically water) and acts either directly on the fire or on the equipment exposed to heat radiation [67]. In the first case, EEI aims at suppressing, or at least limiting, the radiation emitted from the flame. In the second case, the objective is to cool the external walls of equipment in order to avoid its failure. According to previous works dealing with emergency intervention systems [41], EEI is assumed to be able to stop the domino escalation in the plant. Hence, the mitigation action performed by this device is the interruption of the domino chain. Despite this assumption, if EEI is implemented as a protection, the escalation can still occur since the model takes into account the possible failure on demand of the EEI (i.e. PFD=0.1).

Moreover, the effectiveness of the EEI depends on its time of intervention, namely time to final mitigation (TFM). In fact, the emergency teams need time to receive the alarm and start the pre-planned emergency procedures, which are, in general: to convene the teams, to collect the resources, to drive to the site, to deploy the equipment, to start the operations of water cooling/fire control, and, if needed, to carry out extra set-up operations [68]. The total time from the start of the fire to the suppression of domino chain is TFM and its comparison against the time to failure of each target item determines the EEI effectiveness as follows:

- TTF < TFM: the vessel is expected to fail before the beginning of the safety function. EEI effectiveness for the vessel is null (η=0);
- TTF > TFM: EEI intervenes before the expected failure of the vessel. A unitary value is assigned to EEI effectiveness (η=1).

where *TTF* is the effective time to failure of the vessel accounting for the presence of SBs (see Eq. (5)). As mentioned in Section 2.3, this procedure determines the assignment of the discrete probability gate (type "c" in Fig. 3) to the EEI.

2.4. Implementation of safety barriers in the agent-based model

The agent-based modelling relies on two main components, namely: an "environmental" model and an "equipment agent" model developed for each equipment item, resulting in a set of agent models.

The environmental model stores the settings for the surrounding physical environment with particular reference to meteorological parameters (i.e., atmospheric temperature, pressure, humidity, and other parameters that influence the consequences extent of the scenarios [64]) and information related to the considered industrial establishment, such as: the layout, the number/type of the equipment, and the heat radiation emitted from/received by each equipment item during the domino events sequence.

The agent model is associated with the equipment involved in the domino events sequence. An agent is developed for each equipment item and the model describes its interaction with the other variables, which are the other agents and the environment. For the sake of exemplification, a scheme of the dynamic behaviour of the agent model is shown in Fig. 4 and explained in the following.

2.4.1. Inputs of the agent model and simulation timeline

Fig. 4 shows the agent models implemented for atmospheric and pressurized vessels considering both the models for unprotected and protected equipment. Only the flammable effects associated to the stored/processed substances are considered; however, the analysis may be extended to other types of substances and related effects (e.g., toxic, corrosive, etc.).

The agent remains in normal state (N) until an external event (i.e., a fire) affects the vessel. In the agent-based model terminology, this occurs when an external event sends a "message" containing the heat flux information to the vessel. The message received by the agent represents the physical vector that is affecting the vessel, namely the heat flux (Q_r) from a distant or engulfing fire. Each message is linked to a time step, which is determined by the equipment *TTF*. An example of timeline and associated dynamic domino sequences is given in Fig. 5 for a hypothetical case considering three storage tanks (i.e. A, B, and C).

The domino chain shown in Fig. 5 follows discrete time steps. Each time step (t_0 – t_4 in Fig. 5) corresponds to the TTF of each equipment as reported in the description row in Fig. 5. In each run, the algorithm randomly assigns the value of the probabilities of the ETA and follows one of the dynamic domino sequence shown in the last row of Fig. 5.

The domino sequence DS01 shown in Fig. 5 is described in the following. At time t_0, the tank A receives an initial event (*InitEv* in Fig. 5), which generates a pool fire in tank A, and tank A sends a message of emitted heat flux to the target tanks B and C (Q_{em} in Fig. 5). The algorithm estimates the *TTF* of target tanks B and C and sets two time steps in correspondence to the *TTF* of the tanks (t_1 and t_2 for tanks B and C, respectively, in Fig. 5). Then, the time evolves from t_0 to t_1 and the model evaluates the escalation gate through the probability of damage of the reference tank (tank B for t_1, in Fig. 5) with respect to the incoming heat radiation. For the domino sequence DS01, the escalation occurs for tank B; a secondary scenario is generated and t_1 and a message of emitted heat flux is sent to tank C. For time greater than t_1, tank C receives the heat fluxes both from tank A and from tank B, since the tank/pool fire is considered as constant source. The *TTF* of tank C is updated considering the synergistic effect of the incoming heat fluxes, and a new time step is set in correspondence of the updated *TTF* (t_4 in Fig. 4). Then, the time evolves from t_1 to t_4 and the algorithm calculates the probability of failure of tank C at time t_4. The same approach is used to evaluate all the time steps and the dynamic domino sequences are evaluated according to the escalation gates.

For the evaluation of *TTF*, the agent model gets the specific Q_r from the heat radiation matrix, which is stored in the environmental model. The Q_r values are calculated through integral models [64] and depend on the type of substance and the distance among the equipment items. An example of heat radiation matrix is reported in Appendix B of the Supplementary Materials. As mentioned before, the tank/pool fire is considered to affect the surrounding equipment emitting a constant heat radiation over the time, thus it is considered as a heat radiation steady source. On the other hand, the fireball following the catastrophic rupture of pressurized equipment is modelled as a transient phenomenon and the heat flux emitted from the fireball is limited to its duration.

The algorithm calculates the duration (t_{FB}) of the fireball through Eq. (8) and the maximum fireball diameter (D_{FB}) through Eq. (9) [64]. D_{FB} is used to evaluate whether the fireball is engulfing neighbour vessels:

$$t_{FB} = 0.9 \cdot M^{1/4} \tag{8}$$

$$D_{FB} = 5.80 \cdot M^{1/3} \tag{9}$$

where: t_{FB} and D_{FB} are expressed in s and m, respectively, and *M* is the mass of fuel involved in the fireball, in kg.]. The transient evolution of the fireball is modelled according to the indication of experimental studies [69].

As shown in Fig. 6, the fireball diameter is assumed to grow at ground level from t_0 to t_1 until it reaches D_{FB}. Conservatively, the fireball diameter is assumed to be constant and equal to D_{FB} in the time lapse t_0-t_1. During this phase (t_0-t_1 in Fig. 6), the fireball can either radiate heat to neighbouring units (sending a message of emitted heat flux: Q_{em} in Fig. 6) or impinge other pieces of equipment, depending on its diameter and the layout of the plant. In case a piece of equipment is covered by the fireball, the DAMS-P considers the immediate failure and consequent tank/pool fire for atmospheric tanks and a constant radiative heat flux of 100 kW/m^2 for pressurised equipment. These assumptions derive from the indications reported in [25], based on the analysis of previous accidents and it provides a conservative and simplified screening of domino effect targets. In particular, according to [25], the calculated *TTF* for atmospheric tanks engulfed in the fireball are comparable to t_{FB}, whilst the escalation due to flame engulfment for pressurised equipment is unlikely. Therefore, the immediate failure of atmospheric vessels represents a conservative assumption as well as the immediate ignition of their flammable content after the rupture. Then, from t_1 to t_2, the fireball keeps the maximum size D_{FB} and rises into the air until the flame burns out at time t_3. In this phase (t_1-t_2 in Fig. 6), the fireball can only radiate the neighbour units (Q_{em} in Fig. 6). Finally, for time greater than t_2, the transient phenomenon of fireball ends.

2.4.2. Tank agent model

Once a heat flux message is received by the agent, the effective *Q* received by the equipment and the effective *TTF* can be estimated, considering both the synergistic effect of multiple heat fluxes and the possible implementation of one or more SBs to the agent itself, as well as the case of absence of add-on safety measures. Then, the algorithm estimates the damage probability of a piece of equipment through a literature vulnerability model, based on probit correlation adopted in several previous studies [12,49]:

$$Y = 9.25 - 1.85 \cdot \ln\left(\frac{TTF}{60.0}\right) \tag{10}$$

Y is then converted into the probability of damage (P_d) [52].

The code performs Monte Carlo simulations to obtain statistic results. In this work, the number of replications is set to 10^8. Fig 4 gives a simplified scheme of the implementation of SBs in the agent-based model. It is worth noting that the implementation of SBs in the agent model does not modify the heat radiation matrix and, thus, the environmental model. This means that, once the matrix and the layout of the plant are set, it is easy to introduce different SBs deployment plans and

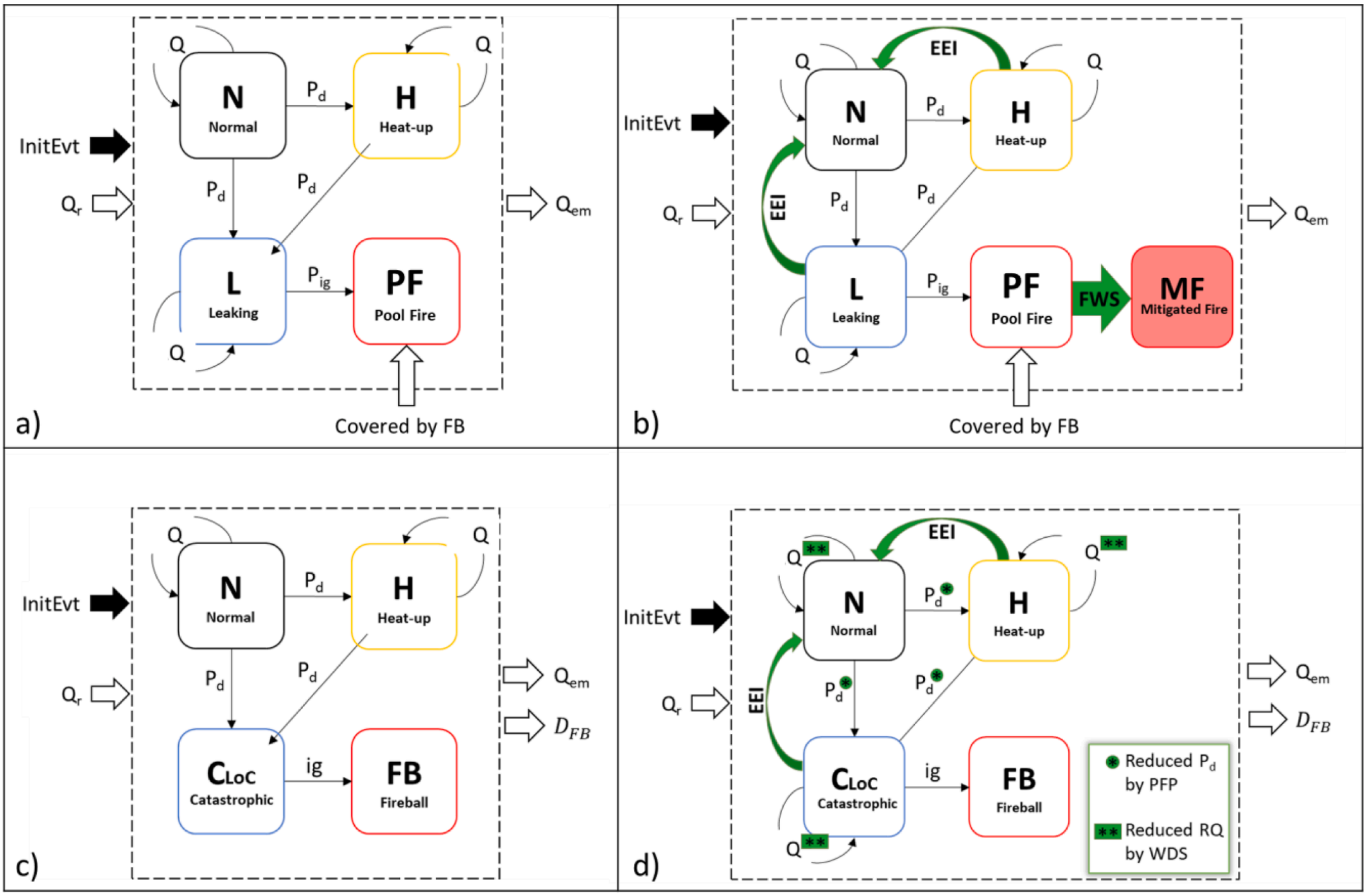

Fig. 4. Agent model schematizations: a) unprotected atmospheric vessel; b) atmospheric vessel including SBs; c) unprotected pressurized vessel; and d) pressurized vessel including SBs.

to evaluate the reduction of the escalation probability associated with each of them.

At time equal to the *TTF* of the tank (see Fig. 5), the DAMS-P evaluates P_d and the tank may evolve either to the heated-up state (H in Fig. 4) or to the damaged state: leaking (L in Fig. 4) and catastrophic (C_{LoC} in Fig. 4) in case of atmospheric and pressurized vessels, respectively. The evolution of the tank state depends on the value of P_d estimated in the random sampling of the Monte Carlo run.

For atmospheric tanks, the agent in the leaking state (L in Fig. 4) indicates that the vessel failed and consequently a spill of flammables takes place, but the ignition is not occurred yet. Then, the DAMS-P evaluates the probability of ignition (P_{ig}) of the release through an ETA, at any subsequent time step. If the release is ignited in the given Monte Carlo run, the atmospheric agent changes to the fire state (F in Fig. 4) and the time step progresses to the given time of ignition. From this time on, the tank gives rise to a pool fire and sends a message of emitted heat radiation (Q_{em}) to all other tanks. Another mean of failure of atmospheric equipment is being engulfed in a fireball (see Section 2.4.1). In this case, the agent that receives the message of a fireball impingement (covered by FB in Fig. 4) and evolves directly from its current state to the fire state considering both P_d and P_{ig} equal to 1, and it sends the message of Q_{em} to all other tanks. For pressurized equipment, when a damage occurs, the agent changes its state to the catastrophic loss of containment (C_{LoC} in Fig. 4) state and, conservatively a value P_{ig} equal to 1 is considered. Hence, the agent evolves to the fireball state (FB in Fig. 4) state and sends both a message of Q_{em} to all other agents and the information for the evaluation of possible impingement of other units, i.e. D_{FB} message.

3. Test cases

A set of four simplified case studies is defined to verify the tool. In each case, the implementation of a single SB is considered and the probability of each possible domino scenario is evaluated trough ETA. It is worth mentioning that the same simplifying assumptions and probabilistic models, both for equipment involved in fires and safety barriers performance, are implemented in the ETA and in DAMS-P. Hence, the verification is aimed at demonstrating the stability and soundness of the numerical tool in a simple application, with limited number of equipment, safety barriers and time steps. Then, the model is extended to the simulation of an industrial case study, considering a complex layout representative of a chemical tank farm located in a chemical cluster.

3.1. Verification case studies

Two simplified plants are defined for the verification of the model, including both atmospheric and pressurized vessels. The layouts are shown in Fig. 7 and Table 2 summarizes the main features of the equipment. Four cases are defined in order implement the contribution of each SB, considering different primary scenarios. Table 3 summarizes the setup of the verification cases and the consequences assessment. The consequences assessments aim at determining the heat flux received by each target tank regardless of SBs. The model accounts for the safety action carried out by the protections through the methodology described in Section 2. For each case, an ETA is developed to estimate the analytical probability of the domino final scenarios. Details on the ETA is reported in Appendix A of the Supplementary Materials. After the implementation of the cases in the DAMS-P, the analytical and simulated

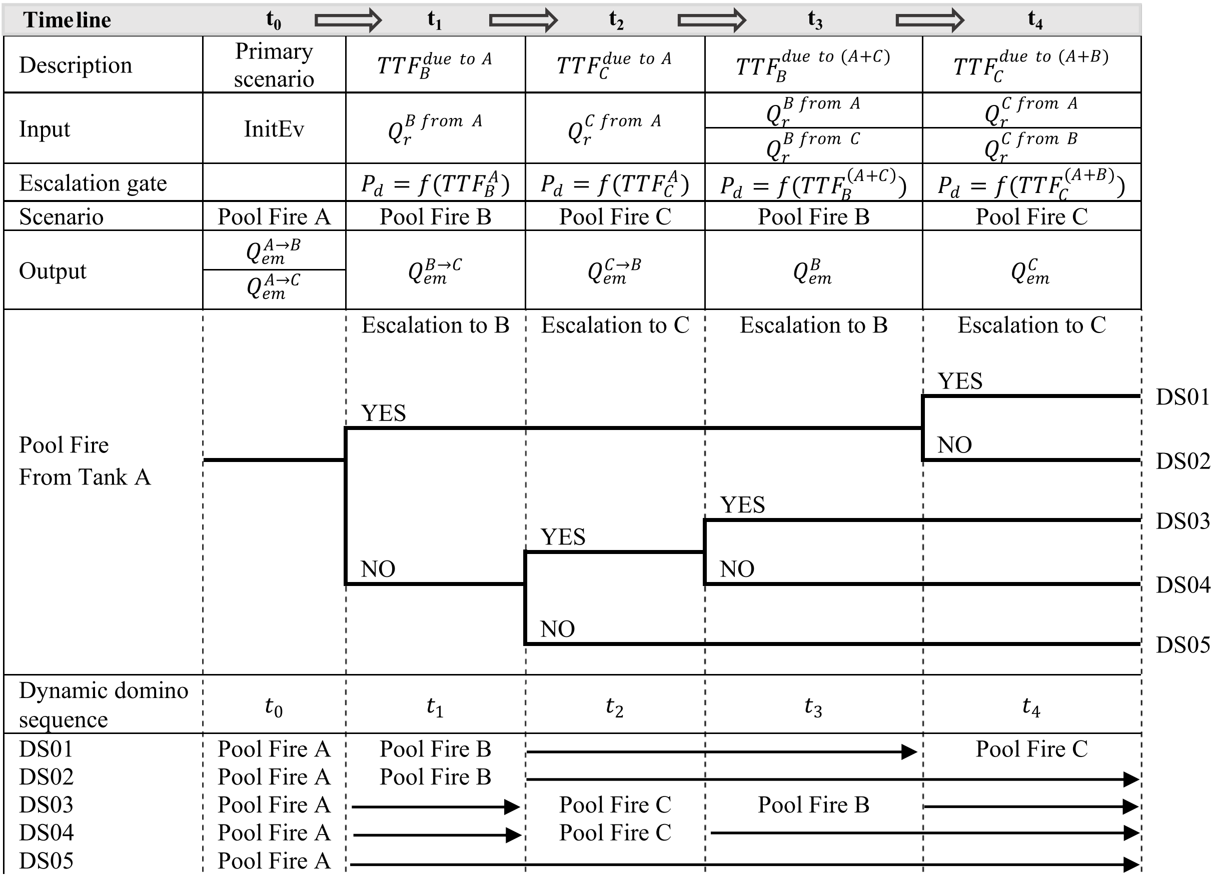

Fig. 5. Example of dynamic timeline and resulting dynamic domino sequences (DS). A, B, and C represent three hypothetical atmospheric tanks. In each time step (t_0-t_4), the model evaluates the probability of failure of the given tank due to the heat flux received from the external fires and then evolves to the following time step. $Q_r^{X\ from\ Y}$ = heat flux received by the tank X from the tank Y; $TTF_X^{due\ to\ Y}$ = effective TTF of tank X due to $Q_r^{X\ from\ Y}$; $Q_{em}^{Y\to X}$ = emitted heat flux from tank Y to tank X; P_d = probability of damage; DS01-DS05 = dynamic domino sequences.

Timeline	t_0	t_1	t_2	t_3
Description	Start fireball Start and growth at ground	$t_0 + t_{FB}/3$ Rise into air End of impingement	$t_0 + t_{FB}$ Burn out End of fireball	$> t_0 + t_{FB}$ No scenario
Input	InitEv			
Scenario	Fireball	Fireball		
Output – to non-impinged **EI**	Q_{em}	Q_{em}	$Q_{em} = 0$	
Output –to impinged **EI**	D_{FB} Atmospheric: $P_d = P_{ig} = 1$ Pressure: $Q_r = 100\ kW/m^2$	End		

Fig. 6. Example of dynamic time line implemented for the fireball scenario. t_{FB} = fireball duration; D_{FB} = fireball maximum diameter; EI = equipment item; P_d = probability of damage; P_{ig} = probability of ignition after tank failure.

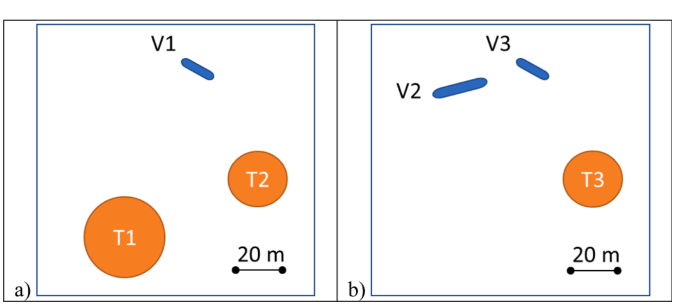

Fig. 7. Reference layouts defined to support model verification of a) case study CS01; b) CS02, CS03, and CS04.

probabilities are compared, and the results of the verification are reported in Section 4.1.

3.2. Industrial case studies

In order to demonstrate the potentiality of the novel tool developed, a large-scale industrial layout is considered. In particular, the chemical tank farm shown in Fig. 8 is implemented in the DAMS-P, featuring different plants and areas. The layout is representative of a CIP in which several tanks store different hazardous substances. The industrial facility consists of 22 storage tanks, with different configurations and different substances. The main features of the tanks are reported in Table 4.

The primary scenario is a pool fire from the cryogenic LNG tank TK01

Table 2
Main features of the equipment implemented for the verification case studies. For the tank ID definition refer to Fig. 7.

Tank ID	Diameter (m)	Height (m)	Capacity (m^3)	Design Pressure (MPa)	Substance	Density (kg/m^3)	Inventory (ton)
T1	31	40	30000	0.1	LNG	422	10128
T2, T3	24	9	4069	0.1	Naphtha	814	3312
V1, V3	3.2	12	100	2	Propane	493	44
V2	3.2	19.4	150	2	Propane	493	67

Table 3
Summary of verification cases, description of the primary scenarios and results of the consequence assessment for primary and secondary scenarios.

ID case	Layout	Primary scenario ID tank	Scenario	ID target tank	Q_{em} (kW/m^2)	SB ID tank	SB	Secondary scenario ID tank	Scenario	ID target tank	Q_{em} (kW/m^2)
CS01	Fig. 7a	V1	Jet Fire	T1	90	T1	FWS	T1	Pool Fire	T2	13
				T2	15			T2	Pool Fire	T1	76
CS02	Fig. 7b	T3	Pool Fire	V2	13	V2	WDS	V2	Fireball	V3	100
				V3	20			V3	Fireball	V2	100
CS03	Fig. 7b	V3	Jet Fire	T3	15	V2	PFP	T3	Pool Fire	V2	114
				V2	90			V2	Fireball	T3	13
CS04	Fig. 7b	V3	Jet Fire	T3	15	All	EEI	T3	Pool Fire	V2	114
				V2	90			V2	Fireball	T3	13

Fig. 8. Layout of the industrial case study featuring the analysis of the tank farm of a CIP. The squares represent the bund areas of the tanks. Tanks ID and features are reported in Table 4

Table 4
Relevant features of the tank farm reported in Fig. 8.

ID	Substance	Operative Pressure (bar)	Diameter (m)	Height (m)	Capacity (m^3)	Filling level (%)	Inventory (ton)	Bund area (m^2)
TK01	LNG*	1	31	40	30175	0.8	10218	2401
TK02	LNG*	1	31	40	30175	0.27	3449	2401
TK03	LNG*	1	31	40	30175	0.58	7408	2401
TK04	LNG*	1	31	40	30175	0.39	4981	2401
TK05	Gasoline	1	39	13	15522	0.74	8615	4900
TK06	Gasoline	1	39	13	15522	0.36	4191	4900
TK07	Gasoline	1	39	13	15522	0.32	3725	4900
TK08	Gasoline	1	39	13	15522	0.42	4889	4900
TK09	Gasoline	1	39	13	15522	0.28	3260	4900
TK10	Gasoline	1	39	13	15522	0.44	5122	4900
TK11	Gasoline	1	39	13	15522	0.46	5355	4900
TK12	Gasoline	1	39	13	15522	0.72	8382	4900
TK13	Styrene	1	14	12	1846	0.59	976	1600
TK14	Styrene	1	14	12	1846	0.23	380	1600
TK15	Styrene	1	14	12	1846	0.76	1257	1600
TK16	Styrene	1	14	12	1846	0.14	232	1600
TK17	Styrene	1	14	12	1846	0.62	1026	1600
TK18	Styrene	1	14	12	1846	0.46	761	1600
TK19	Styrene	1	14	12	1846	0.57	943	1600
TK20	Styrene	1	14	12	1846	0.23	380	1600
TK21	Butadiene	2.3	3.8	22.1	250	0.8	122	248
TK22	Butadiene	2.3	3.8	22.1	250	0.67	102	248

* LNG = Liquefied Natural Gas.

(see Fig. 8), for all the considered cases. The final outcomes in case of domino effect propagation and damage of secondary equipment are confined pool fire[1] and fireball for all the atmospheric and all the pressurized units, respectively. The heat radiation matrix implemented for the industrial case is reported in Appendix B of the Supplementary Materials.

To assess the effect of the SBs on the prevention/mitigation of domino escalation, four add on SBs deployment plans are tested through the model. Each plan considers an increasing level of SBs implementation as reported in Table 5.

The results obtained for the industrial cases are shown and discussed in Section 4.2.

4. Results and discussion

4.1. Results of the model verification

The results of the verification case are reported in Fig. 9, showing the comparison among the analytical probabilities calculated through conventional ETA and the calculated probability of each domino sequence evaluated through the Monte Carlo simulation in DAMS-P. The analytical and calculated probabilities are plotted on the primary vertical axis in logarithmic scale (left-hand side). The relative error between probabilities is reported in the secondary vertical axis (right-hand side).

Table 5
Summary of the industrial cases.

ID case	SB	ID tanks	Description
A	none	TK02-TK22	All tanks
B	FWS	TK02-TK20	Atmospheric tanks
	FWS	TK02-TK20	Atmospheric tanks
C	WDS	TK21-TK22	Pressurized tanks
	PFP	TK21-TK22	Pressurized tanks
	FWS	TK02-TK20	Atmospheric tanks
D	WDS	TK21-TK22	Pressurized tanks
	PFP	TK21-TK22	Pressurized tanks
	EEI	TK02-TK22	All tanks

As can be seen from Fig. 9, DAMS-P reproduces the analytical results with good agreement for probabilities higher than 10^{-4}. In fact, the relative error between the analytical and simulated probability is lower than 0.6% as long as the probability is higher than 10^{-4}. Then, a first peak (relative error > 1 %) is recorded for analytical probabilities lower than 10^{-4}. As the credibility of scenario decreases, the relative error increases. A relative error greater than 10% is recorded for eight scenarios, with a maximum of about 57% for scenario CS01.01.

The comparison against the analytical results from ETA points out the benefit of the simulations. In fact, the analytical resolution of an ETA for a simple layout (i.e. three tanks interacting through only one primary scenario and two secondary scenarios) leads to a large number of domino sequences: 17 for case CS04 and 11 for the other cases. The verification procedure highlights that the estimation of the probability in a domino accident introduces a high level of complexity even for the simplest system. Therefore, a numerical simulation is crucial in the quantitative assessment of the accident propagation chains.

The relative errors obtained in the verification may be due to the low probability and the number of replications; however, the tool allows the fast and conservative analysis of the system. Concluding, the DAMS-P is in good agreement with analytical data for probabilities higher than 10^{-4} and, however, for lower probabilities the tool provides reliable results considering the absolute value of scenarios.

4.2. Results of the industrial case

The results of the industrial case are shown in Fig. 10, in which the probabilities of tank damage and of secondary fires are reported for different SBs deployment plans. The time distributions of having secondary fire from each tank, with respect to different plans, are presented in Fig. 11. The results highlight the effective role of SBs in the risk reduction/mitigation of cascading events in CIPs.

In absence of protections (plan A), the probabilities of being damaged and generating secondary fires are equal to 1 for all atmospheric tanks (TK02-TK20) and greater than 0.9 for the pressurized tanks (0.91 and 0.95 for TK21 and TK22, respectively). Moreover, the model estimates high probabilities of failure and ignition (i.e. greater than 80%) of all atmospheric tanks after 2 minutes and of all pressurized tanks after 6 minutes from the beginning of the primary fire (see Fig. 11). This may be due to the high values of heat radiation obtained

[1] The pool fire is considered to be confined in the bund area shown in Fig. 8

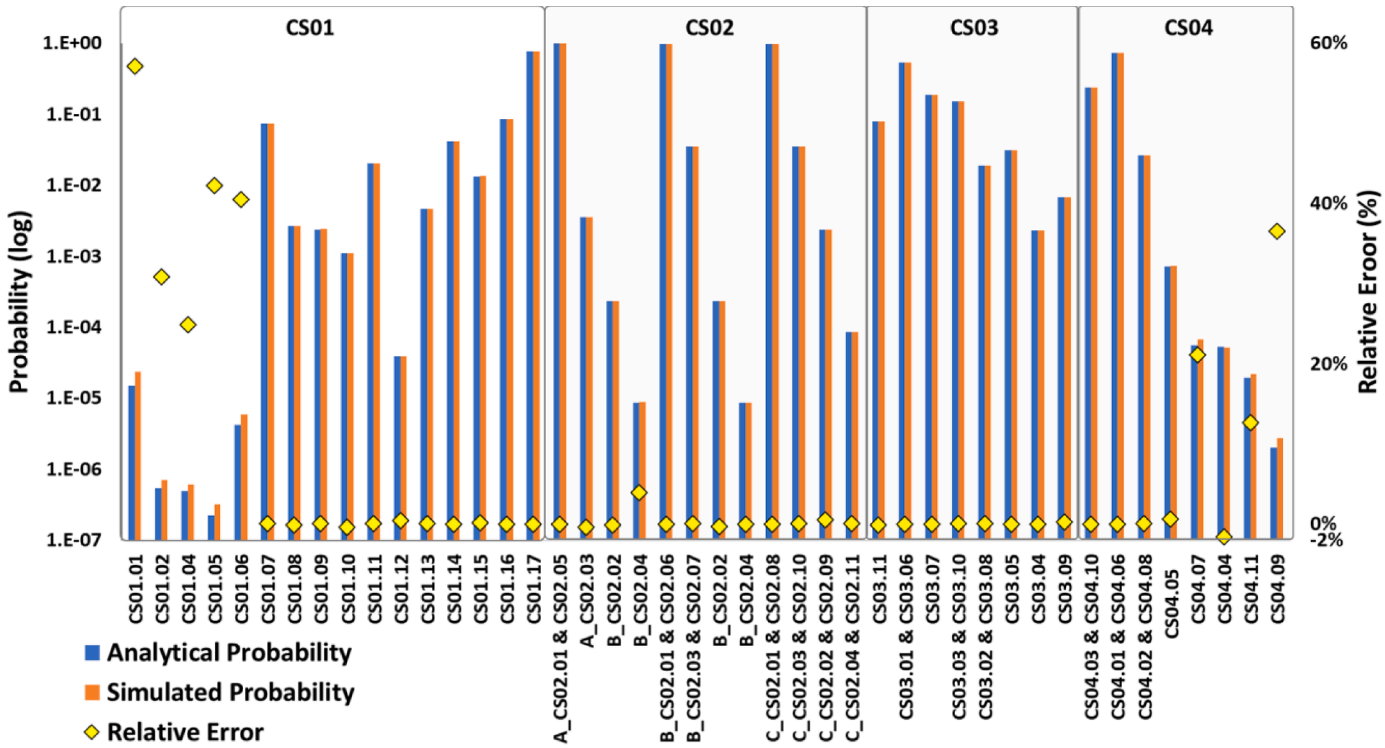

Fig. 9. Comparison of the analytical results and the probabilities obtained through the DAMS-P code, for the verification cases. The ID of the domino sequences are coded as CSXX.YY, where XX denotes the reference case from CS01 to CS04 as shown in Table 3 and YY indicates the different domino outcomes is reported in Appendix A of the Supplementary Materials.

from the primary fire that result in great probit values (i.e. Y>8). Such a short lapse of time for pressurization and possible failure is confirmed both by past accidents, such as the LPG tank explosion occurred in Bologna (Italy) in 2018 [56], previous fire tests carried out on small to medium scale tanks [55,70,71], and recent computational fluid dynamic studies [55,56,72,73], to which the Reader is referred for comprehensive details on the analysis of the pressure build up in vessels exposed to severe fires.

For atmospheric tanks, the implementation of FWS slightly reduces the likelihood of domino propagation. In fact, plans B and C still result in an almost unitary probability of escalation/secondary scenarios, for all atmospheric tanks. The FWS acts on the fire, reducing its emitted heat radiation. Despite the mitigation action of the FWS, the primary LNG pool fire from TK01 severely affects the atmospheric tanks behaviour resulting in high damage probability (i.e. 0.98, see Fig. 10). However, the implementation of FWS affects the probability of having secondary fires from atmospheric equipment in a given time range. The expected failure time of target tanks remains short (i.e. 3-5 minutes), however, it almost doubles compared to the case without SBs (plan A). Effects of FWS deployment (plan B) are more noticeable for pressurized tanks. For pressurized equipment, the probabilities of being damaged/secondary fire in plan B decrease by 30 – 40 % with respect to plan A. Moreover, the expected ignition time after failure of pressurized tanks reaches 10 minutes.

The implementation of passive protections on TK21 and TK22 (plan C) determines a low probability of escalation for the pressure vessels (i.e. lower than 0.05). The additional time provided by PFP before the tank failure results in a safe scenario, in which the pressurized equipment is not expected to generate secondary scenarios (i.e. Y<2, thus indicating low escalation probability).

Finally, deployment plan D results the most effective. In this plan, all SBs are employed: FWS on atmospheric tanks, PFP on pressurized equipment, and intervention of external emergency team. The EEI time of intervention is set assuming that a dedicated team is already located on the cluster and there is availability of water sources on the site, with possibility of using the fire-fighting devices located close to the target tank (i.e., foam monitors, both fixed and portable). Given these assumptions and according to previous works dealing with the analysis of emergency response [66,74,75], a time of 5 minutes from the starting of the primary fire may be set.

The probability of escalation keeps values lower than 0.05 for pressurized tanks, due to the PFP as for plan C. For atmospheric tanks, the EEI safety action determines a significant reduction of the probability of escalation. In fact, the relative reduction of probability of domino propagation ranges from 8 to 86%, which are the values obtained for TK02 and TK19, respectively. However, despite the implementation of EEI, the atmospheric tanks that are in the proximity of the considered primary fires (i.e. TK02-TK06) still show high escalation probabilities (up to 0.9). EEI stops the domino chain with the intervention of the team in 5 minutes from the starting of the primary fire. Hence, the probability of having secondary scenarios after 5 minutes is null for all vessels (see Fig. 11).

It is worth mentioning that in case of absence of dedicated teams and fire-fighting agents located on the site, (thus, relying only municipal fire brigades) the EEI time of intervention may be considerably higher, i.e., up to 30 to 60 minutes, depending on the necessary amount of water and distance from the site [41], thus obtaining probabilistic results similar the ones of case C. Hence, the results highlight that for quick evolving escalation events, such as the one described in the case study, the need of improving emergency team's intervention trough specific training, as well as strengthening add-on hardware barriers with optimized maintenance and inspection plants, is of utmost importance for preventing domino effect escalation.

4.3. Discussion

The results of industrial case demonstrated the potentiality of DAMS-P to support the probabilistic assessment of domino events in complex

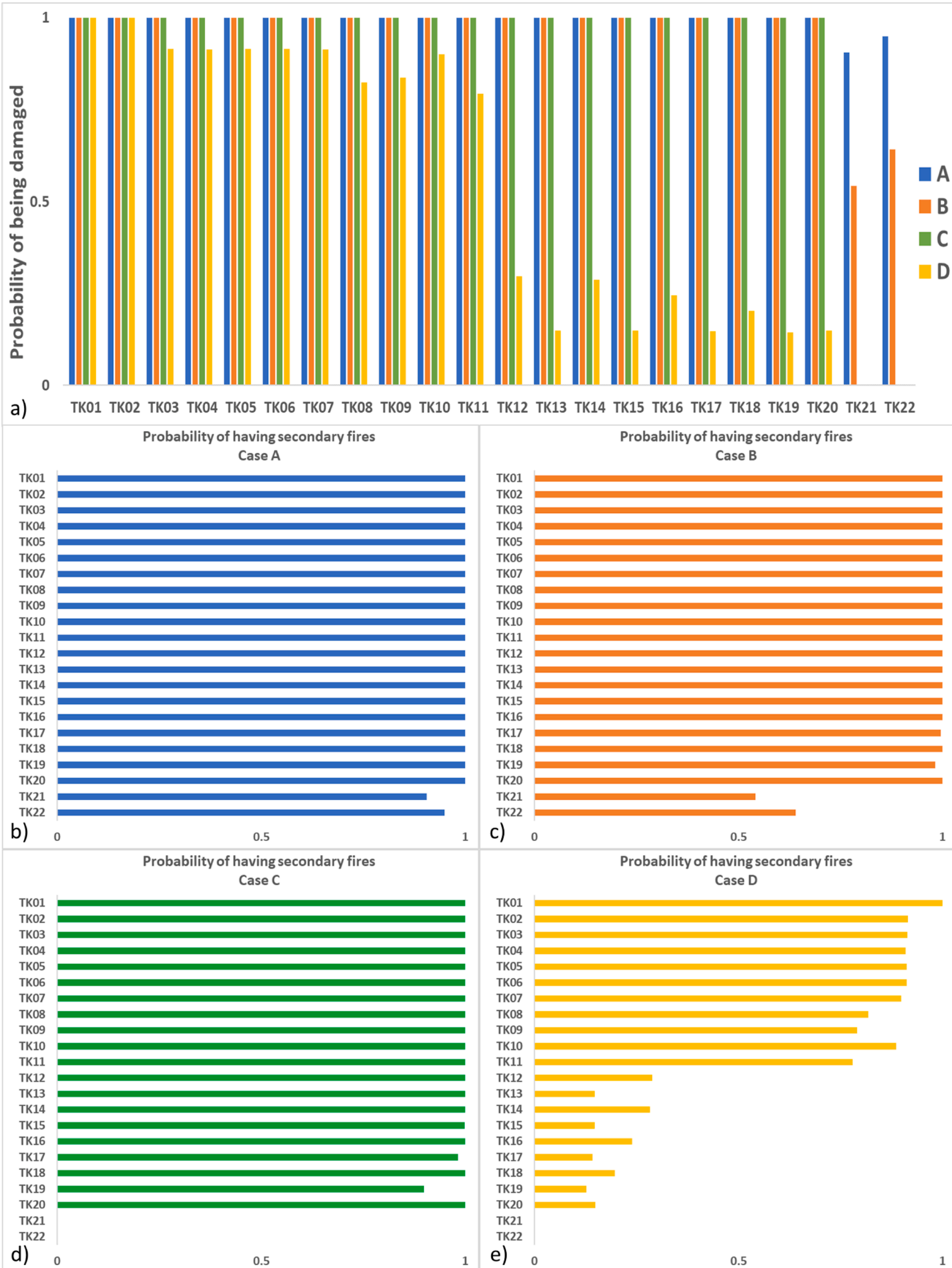

Fig. 10. Results of the industrial case study implemented in tool, a) probabilities of being damaged of each tank; b), c), d) and e) probabilities of having secondary fire of each tank in deployment plan A, B, C, and D as defined in Table 5.

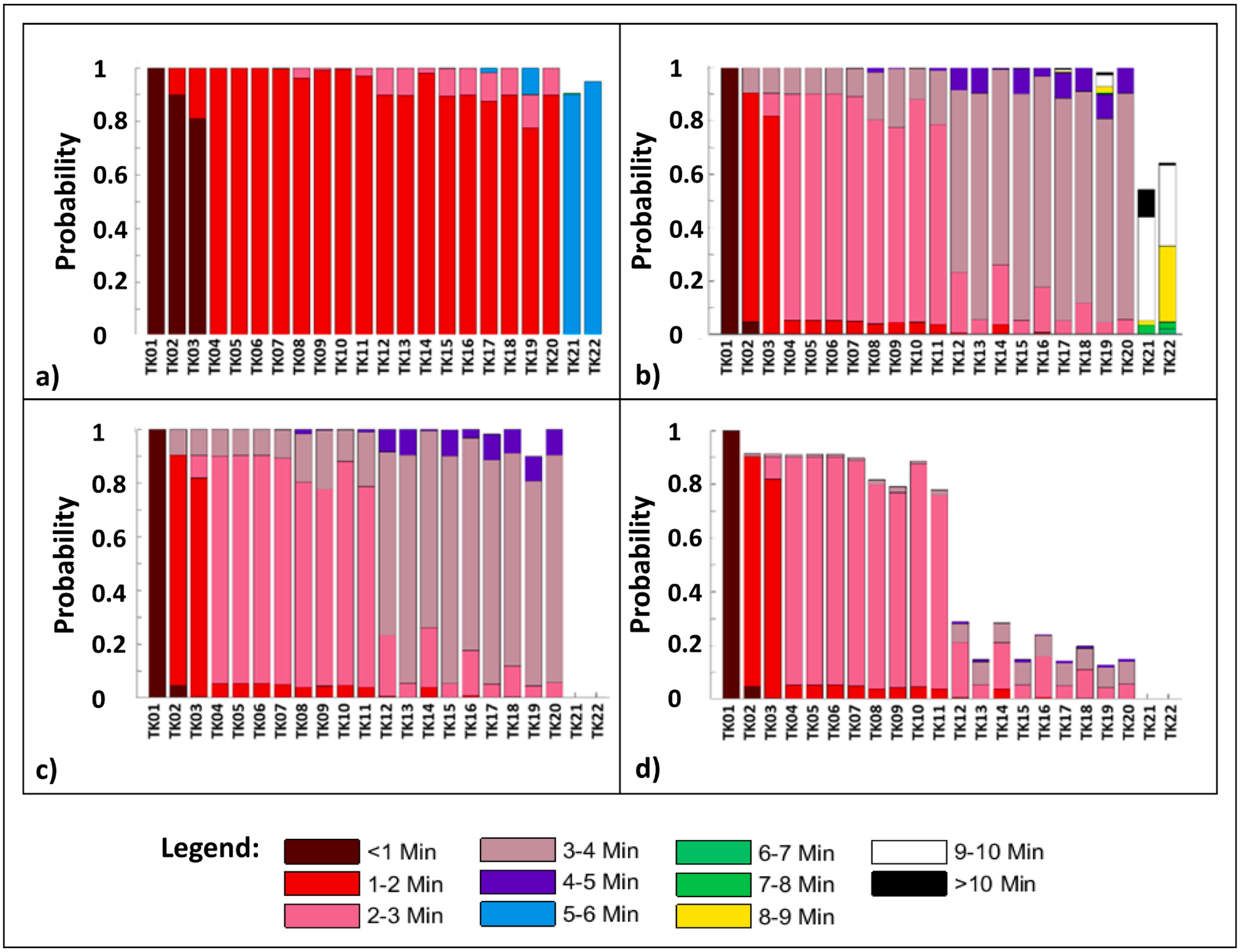

Fig. 11. Results of the industrial case study implemented in DAMS-P. Time distribution of the probability of having secondary fires (i.e. failure of the tank and ignition of the released substance) in a given time range (see Fig. 5 in Section 2.4.1) of each tank, with respect to different deployment plans for safety barriers defined in Table 5; a) case A, b) case B, c) case C, and d) case D with TFM = 5 min.

tank farms. The approach allows for the implementation of different tanks types, substances, and configurations. Due to the plant complexity, the safety improvement process of the whole system is not straightforward. The implementation of safety barriers in the model represents a useful tool for the management and optimization of add-on protection measures of storage sections of chemical clusters. In fact, the model allows comparing different plans for the implementation of protections. This constitutes a possible support to the safety-based decision-making process, both considering the design phase of industrial facilities, when add-on safety barriers need to be selected, and the operation lifecycle of existing plants, dealing with the improvement of maintenance and inspection plans. In particular, DAMS-P may be implemented in the risk-based inspection framework suggested in the CEN Standard EN 16991:2018 [76] in order to design risk-based maintenance strategies, both in the input phase and in the improvement of inspections.

Firstly, the results allow for the risk prioritization of the plants, the equipment, and related components. This represents a critical input to the planning of the inspections. Secondarily, the Standard [76] suggests the implementation of a "computerized maintenance management system" as the key tool for a modern maintenance organization, and DAMS-P may be introduced in the system as a database for the failure modes, the failure rates, and the associated consequences for the plant/CIP risk assessment, with particular reference to domino effect prevention and/or mitigation. Thirdly, as the last activity of a maintenance work is the analysis of the results, DAMS-P may support the comprehensive evaluation of the reliability of the safety systems to be included in the monthly/yearly inspection reports. Therefore, the maintenance management system can be improved by the use of DASM-P.

Fig. 2 summarizes the application of DAMS-P results in practical cases and possible end-users. The site plant HSE manager may take advantages from the quantitative analytic approach of the tool, which supports the definition of the prevention/maintenance policies, the training of personnel, and the systematic evaluation of the performance of different emergency measures. More broadly, risk analysts can use the tool to assess the optimal allocation of protections and the compliance with the regulations on domino requirements. In similar way, the tool may be used by the competent authority for the verification of the safety reports concerning the control of major accident hazards, with focus on interaction between neighbouring plants.

The probabilistic results obtained through DAMS-P can be improved by introducing site-specific data on protection effectiveness and availability, e.g. introducing the probability distributions obtained from the manufacturer or from the field. The main advantage is that, once the agent and the environmental models are set, a large number of customized functions can be implemented without changing the base code. More in general, compared to other methodologies such as dynamic Bayesian network, the agent-based approach does not require the definition of complex conditional probabilities and, hence, avoids the simplification of the physical phenomena and relationships. As discussed in [23], the application of dynamic Bayesian networks is limited to simple cases, thus without accounting for multiple synergistic effects of simultaneous escalation scenarios and complex interaction among safety barriers, as the stochastic variation of agent (i.e., equipment items) and barriers includes the temporal changes in both the probabilities and the probability distributions, which can easily become too cumbersome and intractable. On the contrary, DAMS-P can be managed easily and works well with large-scale layouts, despite featuring several limitations, which may be object of future research.

First of all, the assumptions about the domino escalation may be strengthened, especially considering the role and the evolution of the emergency response. Detailed approaches, such as the one developed in [66,74,77], may be object of future implementation. Moreover, DAMS-P may be extended including other safety devices featuring more complex behaviour.

Next, the characterization of the currently implemented primary and/or secondary accident scenarios may be improved. On one side, the detailed analysis of the fireball evolution and heat radiation exposure may be implemented, in order to reduce the conservative predictions of the code in the present form. On the other side, a broad range of accident scenarios and related physical effects may be object of future development of the code, in order to consider: overpressure and mechanical impulse due explosions, heat load due to direct flame impingement, fragment projection, and toxic dispersions affecting personnel involved in emergency operations.

Finally, the present approach may be extended to a broader set of equipment adopted in CIPs, such as reactors, separators, absorption towers, etc., based on the availability of vulnerability models such as the one adopted in [12] or threshold based approaches [78]. More in general, DAMS-P may be further elaborated in order to adapt to other industrial sectors and critical infrastructures (i.e., energy plants, manufacturing and nuclear facilities, etc.), in need of a simplified tool to describe the interactions and complex accident chains between a numerous industrial equipment.

5. Conclusions

The present work introduces a novel tool to support the detailed probabilistic assessment of mitigated domino scenarios in chemical tank farms. The tool, called DAMS-P, makes a dynamic probabilistic assessment of possible cascading events, accounting for the implementation of add-on prevention and/or mitigation measures. The tool relies on agent-based modelling and simulation, being a bottom-up approach and describing a complex system by simple rules and actions.

DAMS-P, verified against analytical probability evaluations, was applied to several case studies located in industrial tank farms to demonstrate its capability in reproducing complex domino events, considering also synergistic effects, and accounting for the transient evolution of multiple scenarios in presence of safety barriers. This allowed for the identification of the critical barriers and the protection plans, according to their capability in the reduction of the escalation probability. The work provides for the first time an analysis of large-scale layouts and complex interaction schemes, accounting for the degradation and the time evolution of equipment and barriers.

The results virtually provided by the tool may support the decision-making process on safety improvement in CIPs and more specifically chemical tank farms, through the identification of critical plants, equipment, components, and safety barriers.

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CRediT authorship contribution statement

Federica Ovidi: Writing - original draft, Methodology. **Laobing Zhang:** Methodology, Software, Formal analysis. **Gabriele Landucci:** Conceptualization, Supervision, Writing - review & editing. **Genserik Reniers:** Supervision, Writing - review & editing.

Declaration of Competing Interest

None.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ress.2021.107476.

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