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DAMS: A Model to Assess Domino Effects by Using Agent-Based Modeling and Simulation

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Historical data analysis shows that escalation accidents, so-called domino effects, have an important role in disastrous accidents in the chemical and process industries. In this study, an agent-based modeling and simulation approach is proposed to study the propagation of domino effects in the chemical and process industries. Different from the analytical or Monte Carlo simulation approaches, which normally study the domino effect at probabilistic network levels, the agent-based modeling technique explains the domino effects from a bottom-up perspective. In this approach, the installations involved in a domino effect are modeled as agents whereas the interactions among the installations (e.g., by means of heat radiation) are modeled via the basic rules of the agents. Application of the developed model to several case studies demonstrates the ability of the model not only in modeling higher-level domino effects and synergistic effects but also in accounting for temporal dependencies. The model can readily be applied to large-scale complicated cases.

KEY WORDS: Agent-based modeling; computational experiments; domino effect; major accident hazard

1. INTRODUCTION

Domino effects have been responsible for some catastrophic accidents that occurred in the chemical and petrochemical industries.[(1–5)] Although there are multiple definitions of domino effects in the chemical and process industries,[(1,6,7)] this type of accident features a generic schematization with the following elements: (1) there is a "primary event," initiating the domino effect; (2) there is an escalation vector (e.g., fire impingement, heat radiation, explosion overpressure, etc.), facilitating the propagation of the domino effect; (3) one or more secondary accident events, involving one or more target equipment.[(8,9)] In the second element, the influence of synergistic effects should be considered to account for the occurrence of multiple accident scenarios. Through synergistic effect, the escalation vectors of concurrent events are superimposed to identify the possibility of causing damage to other target equipment.

Domino effect occurred several times in the chemical and process industry, featuring high destructive potential.[(10)] Kourniotis *et al.*[(11)] examined 207 major chemical accidents and found that 114 of them involved a domino effect. The existence of domino effects makes assets in process plants dependent on each other, resulting in a systemic risk.[(12)]

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The potential severity of such accident scenarios led to important efforts for the prevention of domino effects,[3,13,14] and also made relevant technical standards and legislation take into account measures to assess, control, and prevent domino effects.

Cozzani *et al.*[7,8] developed a methodology for risk assessment based on the adoption of vulnerability models, which relied on simplified modeling and characterization of the escalation vectors. Khan and Abbasi[15,16] synthesized the quantitative methodologies used in domino effects estimation, and developed a software named "DOMIFFECT" to support the domino effect estimation in complicated situations. Reniers and Dullaert[17] developed a software named "DomPrevPlanning" to support decision making on safety barriers to prevent/mitigate domino effects in complex chemical installations, which succeed in considering multiple domino scenarios. Abdolhamidzadeh *et al.*[9,18] developed an algorithm named "FREEDOM" based on Monte Carlo simulation to assess domino effects. Khakzad *et al.*[19–21] developed a methodology based on Bayesian network both to probabilistically simulate the propagation of domino effects and to identify the most likely sequence of events in a potential domino effect. In their methodology, both the possibility of higher-order domino effects and the influence of synergistic effects were taken into account.

Nevertheless, despite the relevant progress made in the framework of domino effect understanding and modeling, the time dimension and evolution of domino effects, which is critical for emergency preparedness and response,[22] is not systematically accounted for. Khakzad *et al.*[23] developed a dynamic Bayesian network (DBN) methodology to capture both spatial and temporal propagation of domino effects. However, in application of large-scale cases, the DBN model needs a combinatorial-increasing number of conditional probabilities. Furthermore, the DBN model uses a discrete time scheduling method, which has been proved to be not efficient. To this end, the extension of DBN models feature a high level of complexity and demand relevant computational resources for the extension to realistic industrial cases, featuring the simultaneous analysis of dozens of units.

In this work, an agent-based modeling and simulation model—DAMS—is proposed to support domino effect analysis in the chemical and process industries. The aim of this study is to provide a quick yet effective tool for the chemical and process industries to support the emergency response and mitigation strategies. The model is applied to (i) a demonstration case study for verification purpose; (ii) a real industrial setting for illustrating the implementation of the model; and (iii) an intentionally constructed large-scale case study to investigate computational issues. Furthermore, a discussion on computation resources and potential application is also addressed.

2. AGENT-BASED MODELING AND SIMULATION

Agent-based modeling and simulation (ABMS) is a bottom-up approach to study complex systems.[24] Given a system, instead of modeling the patterns, structures, and the system behaviors, the ABMS approach focuses on the basic units (namely, the "agents") of the system, including their attributes and interactions.[24] By performing computational experiments on the agent models, the response and behavior of the global system may be derived.[25] Several examples of ABMS applications in different disciplines and contexts are available in the literature.

Epstein and Axtell[26] proposed an agent-based social simulation model, named Sugarscape, in which multiple agents move, interact, and behave in order to get sources (i.e., sugar). In Epstein and Axtell's seminal book,[26] by defining simple but different rules for the agents, some complex social phenomena such as groups, war, trading, etc. emerged in the Sugarscape model. Since Sugarscape, ABMS has been widely used in social science as well as complex system studies and prediction of pandemics,[27] economic crisis management,[28] and manufacturing.[29] In recent years, ABMS has also been used in the risk analysis domain; some examples among others are the analysis of hurricane evacuation procedures,[30] flood incident management,[31] and defensive resources allocation for spatially distributed networks.[32] However, the potential application in the framework of industrial safety, and especially in relation to domino effect assessment, is innovative and is discussed in this study.

In ABMS, an agent model normally consists of several static attributes and several simple rules. The rules and the interactions of agents should not be complex because simple individual behaviors and interactions can already generate complex system behaviors.

In the case of the application to domino effect assessment, the accident propagation and evolution may be considered as a behavior of the system,

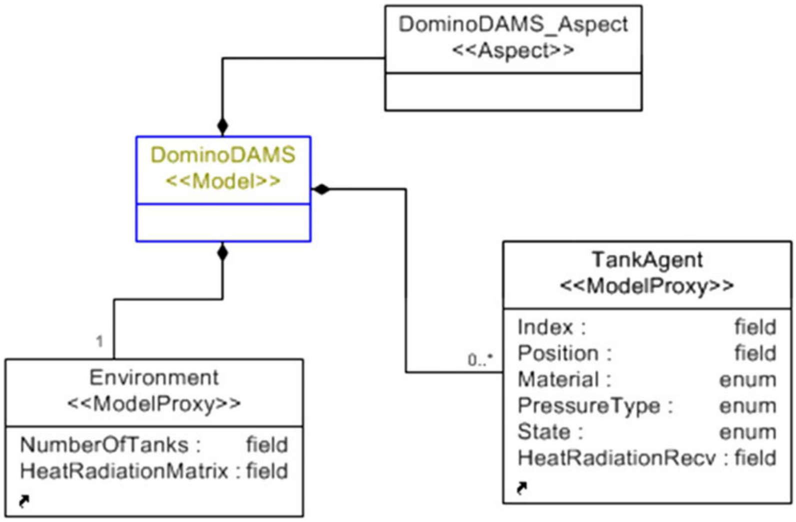

Fig. 1. Framework of the ABMS model for supporting domino effect assessment.

resulting from the interactions (heat radiation propagation and/or overpressure following accidents) of items (target equipment, such as tanks, pipelines, etc.) in the industrial areas. For this purpose, the behavior and interactions of the items should be reproduced with simple rules, which is normally not the case for domino targets. In fact, several studies pointed out the complicating physical phenomena associated with equipment exposed to fire,(33,34) overpressure,(35,36) and missile projection.(37,38) Specific advanced model tools such as finite elements modeling(39) or computational fluid dynamics(40) may be required for a comprehensive detailed assessment. Nevertheless, previous research(33,41) was dedicated to the development of simplified approaches aimed at reproducing the behavior of target equipment exposed to a given escalation vector. Such simple rules and models may be adopted in order to trace the behavior and interaction of single items. Even though the behavior of target equipment during domino effects can be simplified, the domino effect itself is still quite complicated due to several reasons: (i) the probabilistically propagation; (ii) the synergistic effects; and (iii) the dynamic evolution. Therefore, ABMS features a suitable approach to support the analysis of complex domino effects.

3. MODEL DESCRIPTION

3.1. Overview

Among others, the AnyLogic software group, which is one of the most successful groups in developing simulation platforms in the world, defines ABMS as: "from the viewpoint of practical applications agent based modelling can be defined as an essentially decentralized, individual-centric (as opposed to system level) approach to model design. When designing an agent based model the modeller identifies the active entities, the agents (which can be people, companies, projects, assets, vehicles, cities, animals, ships, products, etc.), defines their behaviour (main drivers, reactions, memory, states, ...), puts them in a certain environment, establishes connections, and runs the simulation."(42) Storage tanks are the most frequently involved items in domino effects in the chemical and process industries.(4,43) Some global information such as weather, geography, etc. also plays an important role in domino effects. To this end, active entities in the domino effect assessment by agent-based modeling and simulation (DAMS) model are the tanks and the environment, as shown in Fig. 1. In the following sections, Fig. 2 illustrates the static model of the tank agents; Fig. 4 depicts the tank agent's behavior model; the environment model is given in Fig. 5; connections (or interactions) among agents and between the agent and the environment model are given in Figs. 4 and 6, respectively. Finally, the DAMS model is implemented on three case studies, and Monte Carlo simulation is employed to get the statistic results.

In the following, the presented framework is explained in more detail. For illustrative purposes, the analysis is devoted to domino effects triggered by fire, but the approach can be extended to consider domino effects triggered by overpressure.

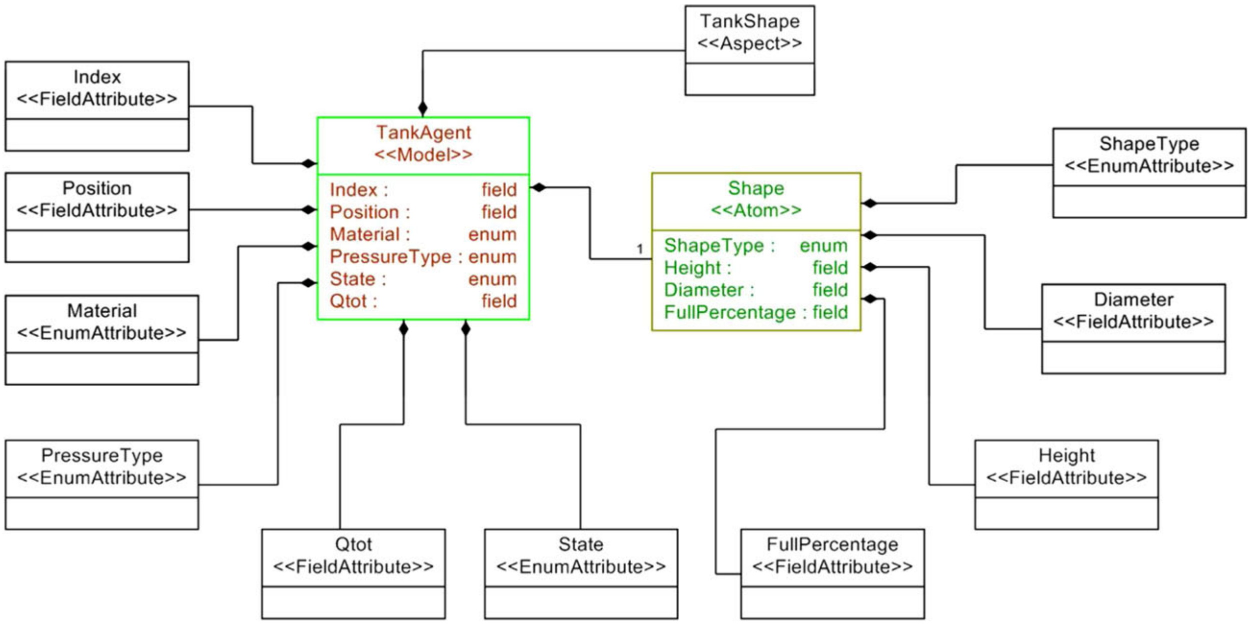

Fig. 2. Static model of tank agent.

3.2. Tank Agent Model

3.2.1. Static Model

Storage tanks (tank agents) are the main agent type involved in the domino effect chain. Because modeling is an abstract form of reality, it cannot capture all the properties of the concerned object; thus, only the properties that are relevant to the modeling and simulation goal should be taken into consideration. Therefore, only the domino-effect-related attributes of a tank are considered in the tank agent models (and the same for other models in this study). All these attributes should be initialized at the beginning of the simulation, given the concerned process plant. The static model of the tank agent is shown in Fig. 2, modeled in the software generic modeling environment (GME).[44]

GME is a configurable toolkit for creating domain-specific modeling and program synthesis environments. It provides interfaces for secondary developers, enabling the users to define their own domain-specific model libraries. In this study, all the static models are graphically shown in the GME whereas the implemented simulations are coded in C++. GME provides interfaces for the model developer to link his or her models coded in some programming languages (e.g., C++) and the graphic icons in the GME.

As shown in Fig. 2, the tank agent model consists of several attributes:

- ➢ Index: unique identity of the tank;
- ➢ Position: coordinates of the tank;
- ➢ Material: nature of the chemical substance stored in the tank, such as benzene, gasoline, etc.;
- ➢ PressureType: indicating whether the tank is an “atmospheric” or “pressurized” tank;
- ➢ Q_{tot}: the accumulated heat radiation that the tank; received from other tanks; more explanation of this attribute is given in the following paragraph;
- ➢ State: the state of the tank, as summarized in Table I;
- ➢ Shape: shape information of the tank, consisting of:

- ■ ShapeType: indicating if the tanks is “vertical cylinder,” or “horizontal cylinder,” or “spherical”;
- ■ Diameter: diameter of the tank;
- ■ Height: the height (length) of “vertical (horizontal) cylinder” tank; this attribute does not apply to “spherical” tank;
- ■ FullPercentage: indicating how full (%) the tank is.

Table I. Definition of the Variables that Characterize the Tank Agent Dynamic Behavior

State	Description
Normal	The tank operates in normal conditions: initial state
Heat-up	The tank is not physically damaged, but due to heat radiation received from external fire the wall and the contents are heating up with consequent pressurization and incipient failure due to structural weakening
Leaking	The tank is physically damaged, thus hazardous materials are released; it is supposed that storage units are provided with a catch basin, which ensures the full containment of the released liquids
Fire	The tank is already on fire in the catch basin

In case at least one tank within the area of interest (AOI)[6] is in failure mode, leading to a primary fire scenario such as a pool fire, one or more neighboring tanks receive heat radiation. Heat radiation exposure may cause a structural damage on each tank. This in turn can result in secondary fires; as a result, possible synergistic effects between the primary and secondary fires should be taken into account. In fact, the resultant heat radiation received by a given target may be increased by the superimposition of the heat radiation of simultaneous fire. This is particularly relevant when a target tank does not receive enough heat radiation to reach failure conditions but, after the secondary failure of other equipment, the resultant heat radiation on the target is increased due to synergistic effects, increasing the possibility of failure.

3.2.2. Dynamic Model

The tank agent has four possible states during the evolution of a domino effect scenario, as summarized in Table I.

In a domino effect, the tank agent can probabilistically transfer from one state to another state, as we will show later in this section. To this end, the formal modeling formalism named "probabilistic statechart" is employed to describe the tank agent's dynamic model.

A probabilistic statechart[(45)] is commonly adopted in order to show the probabilistic transition among the different states. A sample p-statechart showing the inner model of a door is depicted in Fig. 3.

The arrows between states (modules) represent the possible transitions from the initial state to the end state. The content in the square bracket assigned to the transition represents the condition of the transition; the content in the braces represents the actions while the transition happens. For example, only when the condition of "Force" (i.e., someone is opening the door) and "$p < 0.5$" (i.e., he is on the right direction) are satisfied, the transitions "1" and "2" will happen, and if they happen, the door will Compute the opening Angle by "CA." Note that the door is only characterized by a "Closed" or "Open" state; the "P" module is just a judging point.

The states shown in Table I are implemented in the probabilistic statechart, adopted for the modeling and simulation of domino effects, as illustrated in Fig. 4. Table II describes in detail all the conditions and actions in the model.

As shown in Fig. 4, the tank agent is able to react either to an initial event or due to the heat radiation received from an external fire. In the first case, an accidental leak with consequent release of hazardous material is supposed to occur only due to internal causes, such as corrosion, erosion, and accidental pressurization.[(46)] If the tank is damaged, a secondary scenario may occur, which, in turn, may affect surrounding units in the AOI.

The four states in Fig. 4 represent the tank possible states shown in Table I. At a given time, the tank can only be in one of the states listed in Table I. This implies that the states are mutually exclusive. Fig. 4 also shows that there are two main modules (namely, ProbM and ETA), which are used as judging points, so the tank never remains in these modules.

The ProbM module represents the vulnerability model, based on which the tank agent model can evaluate the probability of being damaged. The vulnerability models for heat radiation exposure based on Probit models developed by Landucci *et al.*[(33)] are adopted. Table III summarizes the vulnerability models, based on a simplified correlation for the estimation of time to failure, e.g., the time lapse before the eventual failure of a target tank since the start of an external fire. More details on the failure model of tanks are discussed in Appendix A.

In Equations (1) to (3), ttf represents the time to failure (in seconds); Q denotes the total heat radiation received by the tank (in kW/m^2); V denotes the volume of the tank (in m^3); Y denotes the

[6]Area of Interests (AOI), defined by the U.S. military, is the area of concern to the commander. Hereby we use it to describe the areas affected by the domino effects.

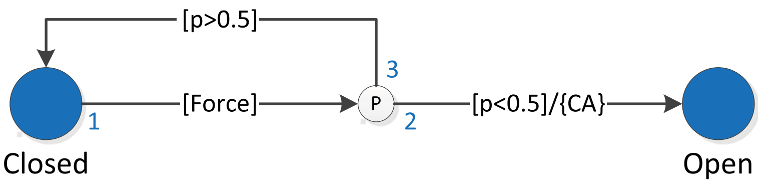

Fig. 3. An illustrative p-statechart model showing door opening.

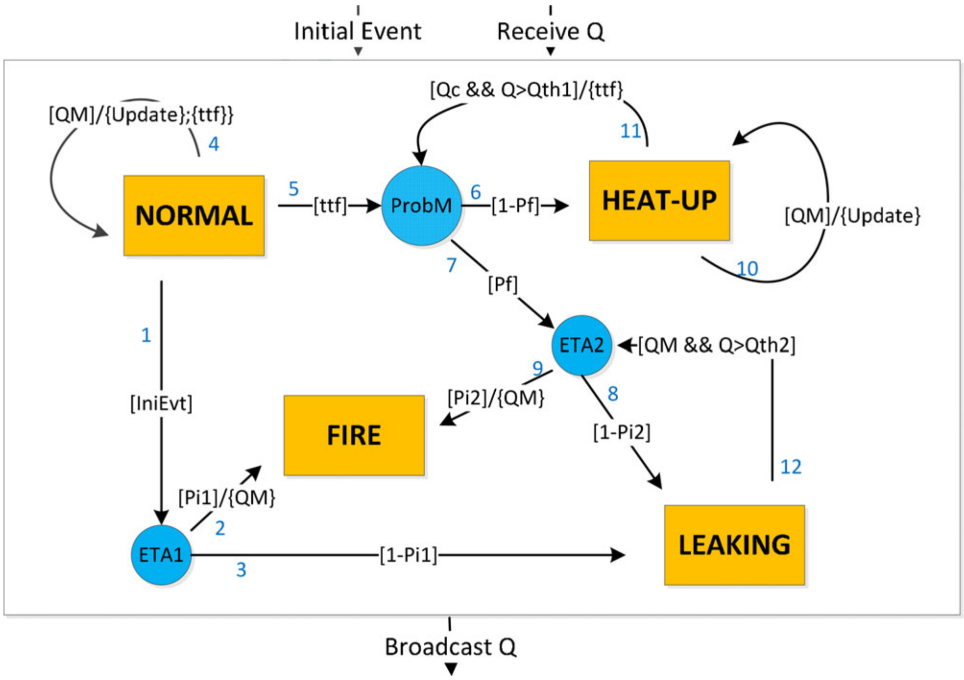

Fig. 4. Tank agent—the dynamic model statechart ("Broadcast" indicates that the "on fire" tank will transmit heat radiation to all other tanks within the AOI).

Table II. Description of Agent Behaviors and Parameters Depicted in Fig. 4

Name	Definition	Details
QM	Heat radiation propagation message	The sender of this message is the tank in "FIRE" state (transitions 2 and 9); the receivers of this message are all the other tanks that are not in "FIRE" state (transitions 4, 10, and 12).
UPDATE	Update Q_{tot}	Updating Q_{tot} by adding the received heat radiation.
Qc	Q_{tot} changes	–
ttf	Time to failure	The time to failure is the time lapse between the start of the fire and the failure of a target vessel. It is computed through the simplified correlations reported in Table III and Appendix A.
P_{f}	Damage probability	This probability is evaluated according to the procedure summarized in Table III.
IniEvt	Initial events	Internal process failure, due to corrosion, accidental pressurization, operator mistakes, etc.(46)
P_{i}	Probability of immediate ignition	P_{i1}: to be selected when there is no tank on fire within AOI. P_{i2}: to be selected when at least one tank is on fire within AOI.
Q_{th1}, Q_{th2}	Threshold of heat radiation	Q_{th1}: when the tank is already in a HEAT-UP state, the threshold of judging whether to use the Vulnerability Model. Q_{th2}: when the tank is LEAKING, the threshold of judging whether to use ETA2. In this study, we set both Q_{th1} and Q_{th2} equal to a constant small number, as $Q_{\mathrm{th1}} = 1\ \mathrm{kw/m^2}$ and $Q_{\mathrm{th2}} = 1\ \mathrm{kw/m^2}$.

Table III. Summary of Vulnerability Models (Heat Radiation Effects) Adopted for the Assessment of Vessel Damage Probability due to Fire

Type of Tank	ttf correlations	Probit model
Atmospheric	$\ln(ttf) = -1.13\ln(Q) - 2.67{\times}10^{-5}V + 9.9$ (1)	$Y = 9.25 - 1.85\ln(\frac{ttf}{60.0})$ (3)
Pressurized	$\ln(ttf) = -0.95\ln(Q) + 8.85V^{0.032}$ (2)	

Probit value. In previous research,[47] a "threshold criteria" has been proposed, where if the received heat radiation was less than a threshold heat radiation, it could not make a credible damage and thus would be ignored. However, in this study, we do not perform a threshold criteria check, assuming that even if a target tank receives less heat radiation intensities, it still might be involved in the domino effect, especially due to the influence of synergistic effects in large-scale cases.

The ETA module represents the postrelease event tree (see Appendix B) to determine the occurrence probability of accidental scenarios (explosion, fire, dispersion, etc.).[1,46] For illustrative purposes, we only considered pool fire as the possible accident scenario, assuming a null probability of delayed ignition (see Appendix B). Hence, explosions or flash fires are excluded from the analysis.

When the tank is in the "Normal" state (Fig. 4):

(1) it can react to an initial event (transition 1), such as flammable liquid leakage;
(2) it can react to the heat radiation from other tanks (transition 4) and update the total heat radiation Q_{tot} it receives; after updating the Q_{tot}, the agent will compute the time to failure (ttf);
(3) it can compute the probability of being damaged P_{f}, based on the vulnerability model, when the time reaches the ttf(transition 5).

When the tank is in the "Heat-Up" state (Fig. 4):

(1) it can react to the heat radiation from other tanks, and update the total heat radiation Q_{tot} it receives (transition 10).
(2) it can compute the ttf, if the updated Q_{tot} is greater than the threshold Q_{th1} (transition 11). Note that the threshold check here is different from the above-mentioned threshold criteria;[47] in the present study, when this threshold check is being executed, it means that the tank is already heated up. As shown in Table II, Q_{th1} (and also Q_{th2}) is set to be a small value.

When the tank is in the "Leaking" state (Fig. 4):

1) it can react to the heat radiation from other tanks if Q is greater than the threshold Q_{th2} (transition 12).

At the ETA1 module, if there is an ignition, a secondary fire will occur and the tank agent broadcasts heat radiation to all other tanks (transition 2). If there is no ignition, the tank will keep leaking out its content (transition 3). Only the primary tank agent will move to ETA1; thus we can set the ignition probability based on standard literature data, as $p_{i1} = 0.1$.[46]

At the ProbM module, the tank will compute the probability of being damaged (P_{f}) due to fire exposure. In case the tank does not fail, at probability$(1 - P_{\mathrm{f}})$, it will transfer to "HEAT-UP" state (transition 6, in Fig. 4), which means the tank is not physically damaged, but its temperature and pressure are increasing due to the fire. In other words, a deterioration of the tank occurs without compromising its integrity; thus, with no release of hazardous materials. On the other hand, if the tank fails (with a probability P_f), it will transfer to ETA2 (transition 7, in Fig. 4). This means that the tank is physically damaged and an event tree model is applied in order to trace the evolution of postrelease scenario. It is worth mentioning that the domino targets move to ETA2 only as a consequence of fire exposure. Thus, due to the presence of heat radiation, the ignition probability for ETA2 was set higher than ETA1, for illustrative purpose, $p_{i2} = 0.6$.

At the ETA2 module, in case of ignition, a secondary fire scenario occurs ("FIRE" state) and the agent will broadcast heat radiation to all other tanks (transition 9, in Fig. 4). If there is no ignition, the tank starts to/continues the release of hazardous material (transition 8).

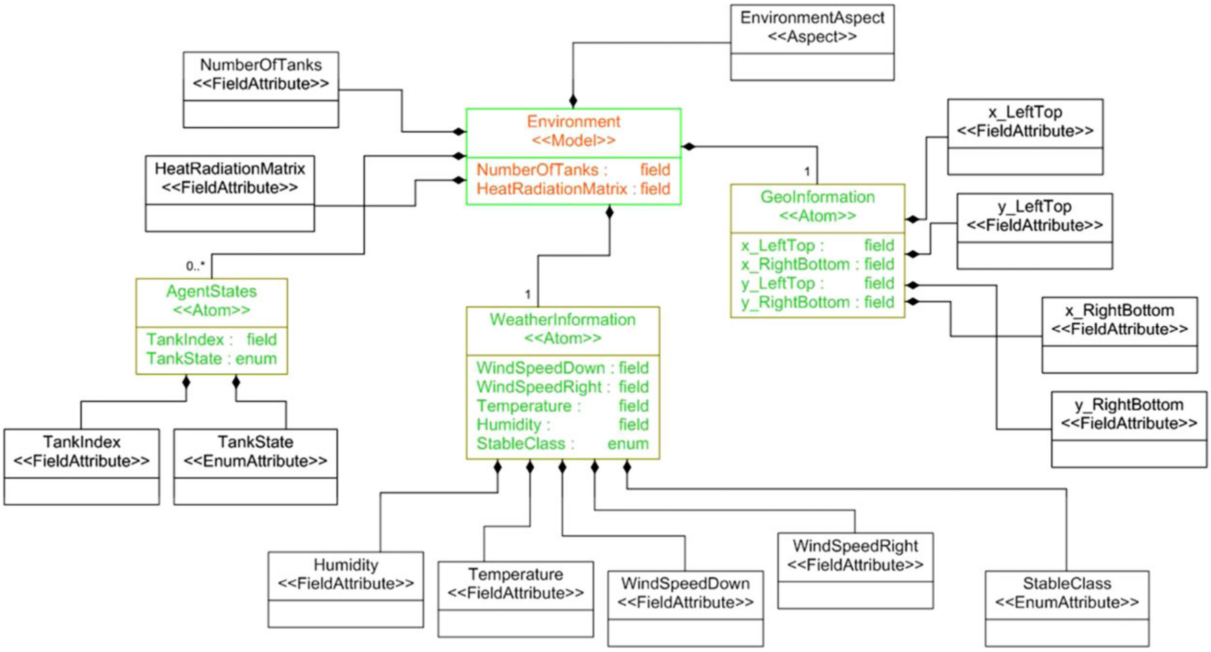

Fig. 5. Static model of the environment model.

3.3. Environment Model

In the present work, the environment model has two functions. One function of the model, which considers the analysis of domino effect evolution, contains the information of the AOI, such as the geographic properties, the weather information, etc. Another function is, on the side of the simulation run, that the environment model acts as an observer, monitoring and storing information about the states of each tank agent.

Fig. 5 shows the static model of the environment model, modeled in GME, whereas the dynamic interaction of the environment model is presented in Fig. 6.

As shown in Fig. 5, the static model of the environment model consists of the global information of all the tanks, as well as some geographic information and weather information. The meanings of all the attributes can easily be understood according to their names, except the "HeatRadiationMatrix." HeatRadiationMatrix is a two-dimensional matrix, whose entry HRM_{ij} represents the heat radiation from tank i to tank j if tank i would be on fire.

Because the environment model manages all the global information, the tank agents need to "Get the required Information" (the GrI line in Fig. 6) from it. For instance, when computing the heat radiation to other tanks, the tank on fire needs to know how many tanks are there in the AOI, and how many of them have already failed. When the tank agent changes state, it needs to "Report the State" change (the ReS line in Fig. 6) to the environment model.

4. DESCRIPTION OF CASE STUDIES

In this section, three case studies are used to demonstrate the application of the DAMS model. Case study #1 is a simplified demonstration case study, aiming at interpreting the correctness of the DAMS model; case study #2 is a real-scale case study composed of 34 chemical tanks, used to show the advantages of the DAMS model, compared to previous models;[23] case study #3 is an intentional constructed case study, aiming at illustrating the extensibility of the model to large-scale cases possibly containing hundreds of tanks in industrial practice.

4.1. Case Study #1: Verification of the Model

In order to test the validity of the model, a demonstration case study is first considered. The simplified example was defined in order to obtain the analytical solution of the problem, thus providing external validation data for the current model.

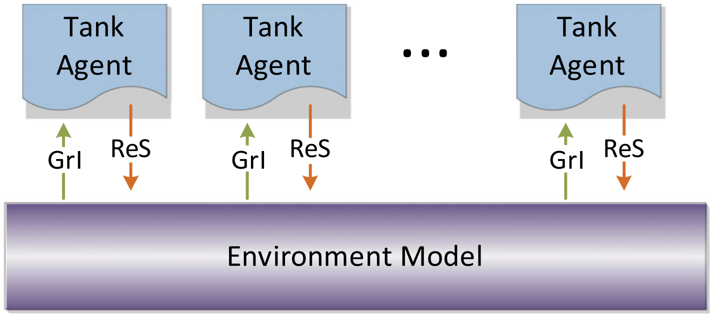

Fig. 6. Schematization of the dynamic interactions among agents and environmental model.

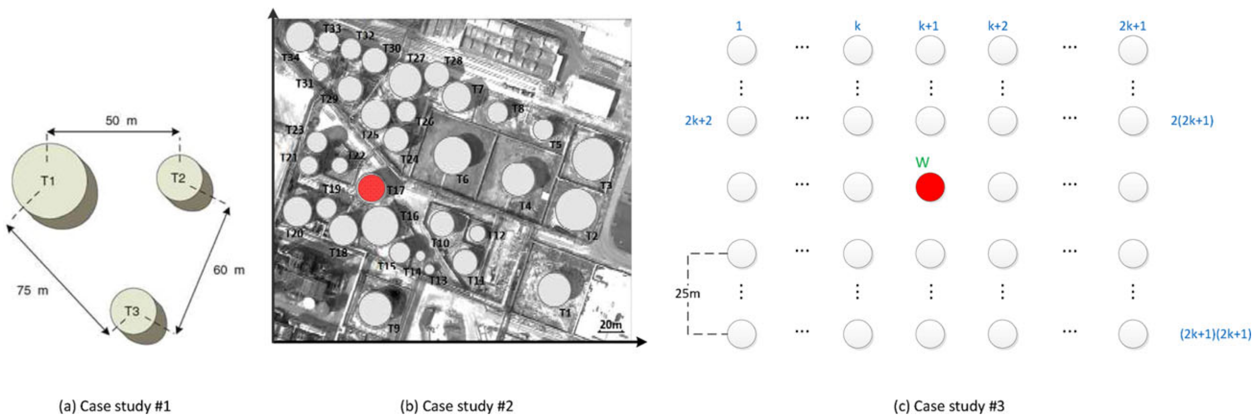

Fig. 7. Layout of the case studies considered in Section 4.

Table IV. Features of the Tanks Considered for the Analysis of Case Study #1 and Consequence Assessment of the Primary Scenarios

ID	Coord. (x;y in m)	Substance	Diameter (m)	Height (m)	Volume (m^3)	Initial Event Frequency (y^{-1})	Radiation on Each Target (kW/m^2)		
							T1	T2	T3
T1	0.0; 59.8	Hexane	20	10	3,142	1×10^{-4}	–	23.8	15.7
T2	50.0; 59.8	Benzene	14	8	1,232	1×10^{-4}	25.5	–	26.4
T3	45.3; 0.0	Benzene	14	8	1,232	1×10^{-4}	9.54	12.5	–

4.1.1. Description of the Tank Farm

The tank farm considered for the analysis of the simplified case study is represented in Fig. 7(a) (modified version of the case used in Khakzad *et al.*[20]) and consists of three atmospheric storage tanks storing flammable liquids; the features of the tanks are summarized in Table IV. The same type of failure due to internal process causes was assumed to affect every tank, causing the release of the entire liquid content in the catch basin in 10 minutes.[48]

The ALOHA software for consequence analysis[49] allowed estimating the heat radiation caused by the pool fire following the ignition of the flammable material. The following meteorological conditions were considered for the analysis of the case study: stability class D, wind at 5 m/s blowing from North, ambient temperature of 25 °C, and 50% relative humidity. The results of the consequence assessment are also reported in Table IV. It is worth noting that the outputs of the ALOHA software (i.e., the heat radiation matrix) are used as the inputs of the DAMS model. By setting critical conditions for the ALOHA software, the output heat radiation would also be high, thus the domino risk assessed by the DAMS model is the worst result as well.

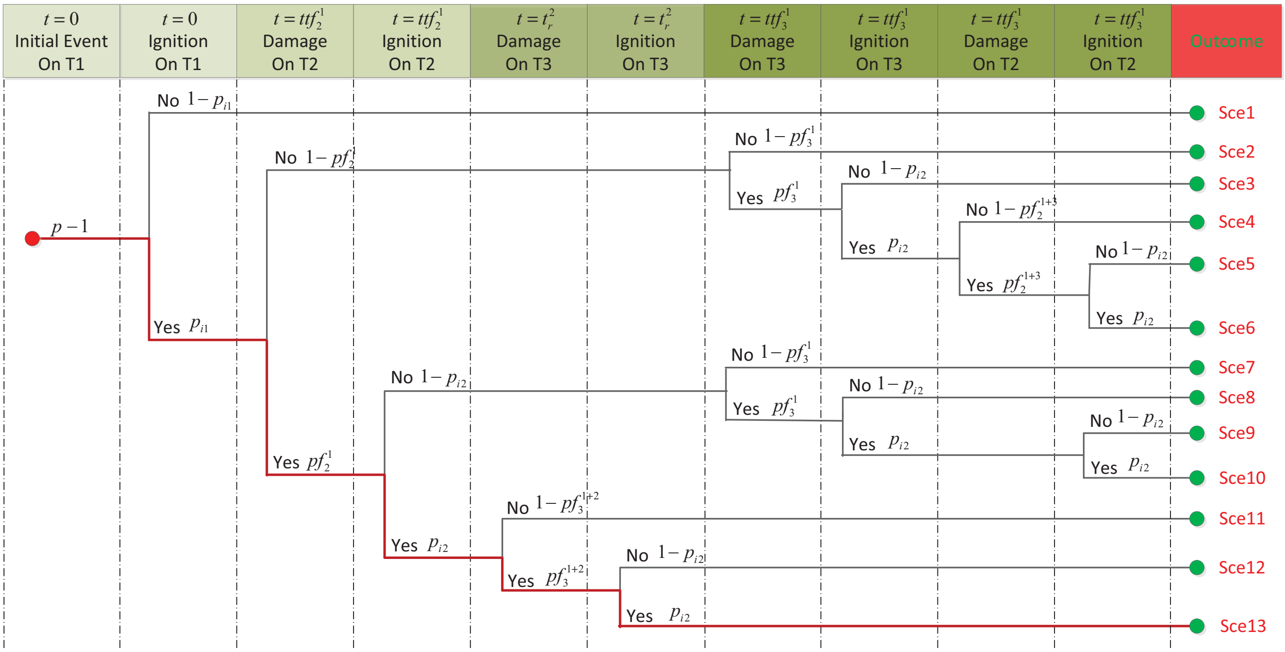

Fig. 8. Dynamic event tree analysis: analytic result of the simplified case study.

For illustrative purposes, T1 is assumed to be tagged with an initial event.

4.1.2. *Analytic Results of Case Study #1*

Fig. 8 shows the analytic results of the demonstration case, based on the dynamic event tree analysis,(50) considering not only the probabilistic dimension, but also the time dimension.

At $t = 0$, there is a probability of p_{i1} that T1 would be ignited. If T1 is ignited, then T2 and T3 would be heated. By employing Equation (1) and data shown in Table IV, we have $ttf_2^1 = 536$, and $ttf_3^1 = 858$. At time $t = ttf_2^1$, T2 would be heated up; thus by employing the vulnerability model (i.e., Equation (3)), T2 would be physically damaged at probability $pf_2^1 = 0.5779$; furthermore, T2 would be ignited at that time by probability p_{i2}. If T2 is also on fire, T3 would receive heat radiation from both T1 and T2. By employing Equation (A.6) in Appendix A, we have $t_r^2 = 631$. At time $t = t_r^2$, T3 would be physically damaged and ignited, at probabilities pf_3^{1+2} and p_{i2}, respectively. Note that while computing pf_3^{1+2} by using Equations (1) and (3), the total heat radiation received (i.e., 15.7 and 26.4 kW/m^2 from T1 and T2, respectively) by T3 should be used as input, obtaining $pf_3^{1+2} = 0.9175$, as further explained in Appendix A.

The above paragraph explains scenario 13; other scenarios can be explained in an analogous way. Table V summarizes all 13 scenarios shown in Fig. 8. Events in the description column are shown as (tank index, state, time), and they are listed according to the time of occurrence.

4.2. Case Study #2: Application of the Model

In this section, we apply the DAMS model to a realistic chemical area containing 34 tanks, as shown in Fig. 7(b). Further information of this case study is given in Appendix D.

Analytical methods such as dynamic event trees and Bayesian networks could be quite complex if they are implemented on this case study. However, the DAMS model proposed in this study can easily be implemented on this case study. Section 5.2 gives some computational results of this case study.

4.3. Case Study #3: Computational Complexity of the Model

Although one advantage of the DAMS model is that the number of replications will not be influenced by the number of tanks (see proofs in Appendix C), the computational time of each replication will increase when the number of tanks increases. In this

Table V. Analytical Solution of Case Study #1

Scenario	Description (L: Leaking; H: Heat-Up; F: Fire)	Probability
Sce1	(1,L,0)	$1 - p_{i1}$
Sce 2	(1,F,0)→(2,H,ttf_2^1)→(3,H,ttf_3^1)	$p_{i1} \cdot (1 - pf_2^1) \cdot (1 - pf_3^1)$
Sce 3	(1,F,0)→(2,H,ttf_2^1)→(3,L,ttf_3^1)	$p_{i1} \cdot (1 - pf_2^1) \cdot pf_3^1 \cdot (1 - p_{i2})$
Sce 4	(1,F,0)→(2,H,ttf_2^1)→(3,F,ttf_3^1)→ (2,H,ttf_3^1)	$p_{i1} \cdot (1 - pf_2^1) \cdot pf_3^1 \cdot p_{i2} \cdot (1 - pf_2^{1+3})$
Sce 5	(1,F,0)→(2,H,ttf_2^1)→(3,F,ttf_3^1)→ (2,L,ttf_3^1)	$p_{i1} \cdot (1 - pf_2^1) \cdot pf_3^1 \cdot p_{i2} \cdot pf_2^{1+3} \cdot (1 - p_{i2})$
Sce 6	(1,F,0)→(2,H,ttf_2^1)→(3,F,ttf_3^1)→ (2,F,ttf_3^1)	$p_{i1} \cdot (1 - pf_2^1) \cdot pf_3^1 \cdot p_{i2} \cdot pf_2^{1+3} \cdot p_{i2}$
Sce 7	(1,F,0)→(2,L,ttf_2^1)→(3,H,ttf_3^1)	$p_{i1} \cdot pf_2^1 \cdot (1 - p_{i2}) \cdot (1 - pf_3^1)$
Sce 8	(1,F,0)→(2,L,ttf_2^1)→(3,L,ttf_3^1)	$p_{i1} \cdot pf_2^1 \cdot (1 - p_{i2}) \cdot pf_3^1 \cdot (1 - p_{i2})$
Sce 9	(1,F,0)→(2,L,ttf_2^1)→(3,F,ttf_3^1)→ (2,L,ttf_3^1)	$p_{i1} \cdot pf_2^1 \cdot (1 - p_{i2}) \cdot pf_3^1 \cdot p_{i2} \cdot (1 - p_{i2})$
Sce 10	(1,F,0)→(2,L,ttf_2^1)→(3,F,ttf_3^1)→ (2,F,ttf_3^1)	$p_{i1} \cdot pf_2^1 \cdot (1 - p_{i2}) \cdot pf_3^1 \cdot p_{i2} \cdot p_{i2}$
Sce 11	(1,F,0)→(2,F,ttf_2^1)→(3,H,t_r^2)	$p_{i1} \cdot pf_2^1 \cdot p_{i2} \cdot (1 - pf_3^{1+2})$
Sce 12	(1,F,0)→(2,F,ttf_2^1)→(3,L,t_r^2)	$p_{i1} \cdot pf_2^1 \cdot p_{i2} \cdot pf_3^{1+2} \cdot (1 - p_{i2})$
Sce 13	(1,F,0)→(2,F,ttf_2^1)→(3,F,t_r^2)	$p_{i1} \cdot pf_2^1 \cdot p_{i2} \cdot pf_3^{1+2} \cdot p_{i2}$

section, we will show the computational time of cases with different numbers of tanks in case study #3.

When the number of tanks increases, it becomes difficult to collect and input all the required data to the model. A typical tank farm is represented in Fig. 7(c) in order to generate typical inputs for the computational time testing. As shown in Fig. 7(c), the tank farm consists of $n = (2k+1)^2$ tanks, and each tank is located on one grid in a $(2k+1) \times (2k+1)$ square.

The tank agents' index and position are given in the figure. We assume that all the tanks are atmospheric vertical cylindrical tanks ($d = 14$m, $h = 8$m) storing benzene. The same environment information used in the simplified case was adopted in the present assessment. The consequence assessment of the pool fire resulting from the failure of each tank was assessed using ALOHA.

We set the middle tank (the red one) as the primary unit W and run $N = 10^6$ replications for increasing the values of k.

5. RESULTS

5.1. Analysis of Case Study #1

Based on the information given in Section 4.1, the tank agents and the environment model were initialized.

When tagged with an initial event, tank T1 has $(1 - p_{i1})$ probability of being in "LEAKING" state. In this case, the simulation would stop since the tank no longer contributes to the domino effect. Thus, such a case is excluded from the simulation. In other words, in the simulation, tank T1 is set on a "FIRE" state, and each simulation result is multiplied with the respective probability of immediate ignition (p_{i1}).

Fig. 9 shows the comparison of the results obtained via the application of the DAMS model against the analytical results described in Table V. As shown in the figure, a good agreement is obtained, with a maximum relative error of 1.66% and a maximum absolute error of 5.2284×10^{-5} in case of running 10^6 replications. Therefore, the present approach is considered reliable and can be extended to the analysis of more complex cases.

5.2. Analysis of Case Study #2

Based on the information given in Section 4.2, we can initialize the tank agents and the environment model. T17 (indicated in red color, in Fig. 7(b)) is set to be the primary unit that is on "FIRE" (as explained above). To make sure that the probabilistic results are reliable on the thousandth, 10^6 replications were used; see Appendix C for further explanation.

Fig. 10 shows the mean time μ ($\pm\sigma$) of catching fire of each of the tanks. For example, T1 is on fire in 500,668 replications among the 10^6 replications, and it might be on fire at different times in each of the replications.

As shown in Fig. 10, because T17 is set as the primary unit, and is assumed "on fire" initially, its time of being on fire is 0 sec. Generally, the nearer a tank to tank T17, the quicker it would be affected by a domino effect, resulting in the roughly "V" shape of

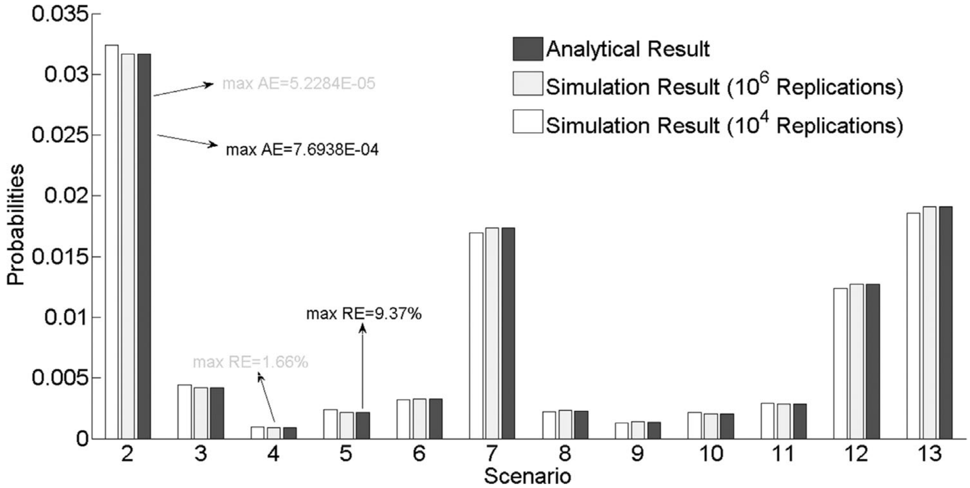

Fig. 9. Results of case study #1. Parity plot comparing analytic and simulation results.

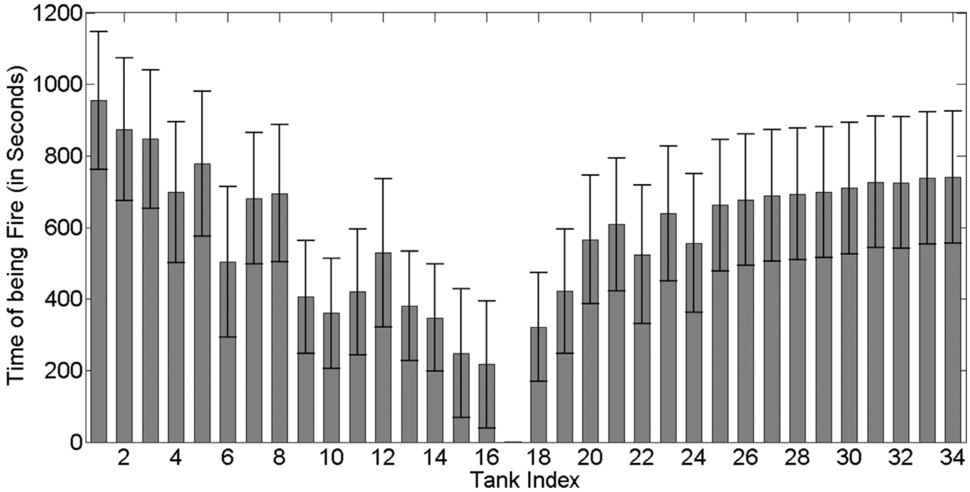

Fig. 10. Time distribution of catching fire of each tank.

the time bars. However, due to the different materials stored in the tanks and different environmental conditions (e.g., the wind direction), the time of being affected is not strictly proportional to the distance from T17.

Fig. 11 shows the probabilities of being on "Fire" of each tank, with respect to different response times. The white bars in (Fig. 11 (a)) show the probabilities of each tank of being fire, under the condition that there is no emergency response at all (and also without (heat radiation threshold check); the light gray bars Fig. 11(a)) show the probabilities of each tank being on fire up until 20 minutes (this knowledge is important as the emergency response teams are usually able to intervene and mitigate the fires within 20 minutes); the medium gray bars (Fig. 11 (b)) show the results up until 10 minutes, while the dark gray bars (Fig. 11(c)) show the results up until 5 minutes.

Fig. 11 shows that, when there is no emergency response (the white bars), the tanks from index 10 to 30 have similar conditional probabilities of being on fire, ranging from 0.9 to 1.0. That is, if we only consider the probabilistic dimension of domino effect, these 20 tanks have similar risks. However, by considering the emergency response time (i.e., the gray bars in Figs. 11(b) and 11(c)), it can be noted that tanks 9 to 11 and 13 to 19 have higher domino risks than the others.

It can be concluded that, if a leakage happens at T17, all the other tanks in this area will have a risk

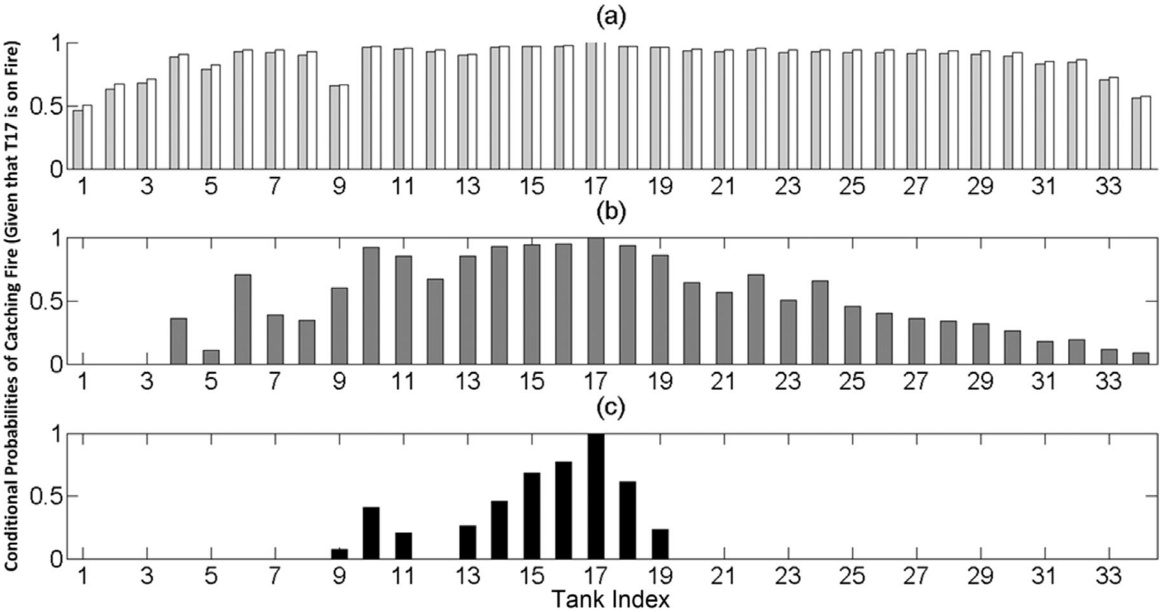

Fig. 11. Conditional probabilities of catching fire of each tank, w.r.t. different emergency response times. (a) In case of no response at all (the white bar) and an emergency response time of 20 minutes (the gray bar); (b) in case of an emergency response time of 10 minutes; and (c) in case of an emergency response time of 5 minutes.

of being on fire at a probability ranging from around 0.05 to 0.1 (recall that with an initial event, T17 will be on "Fire" with $p_{i1} = 0.1$). However, if the emergency response team starts the intervention within 5 minutes after the first fire, the risk of the whole plant will decrease significantly.

5.3. Analysis of Case Study #3

The results of the computational times are summarized in Fig. 12. The computational times in case of $n \geq 169$ are estimated based on 10^4 replications, and are drawn as mean time $\pm\sigma$.

As shown in Fig. 12, the computational time increases exponentially with the number of tanks. In order to implement the model to a realistic case as given in Reniers *et al.*[12] (i.e., $n = 225$), the estimated time would be around 52.32 hours.

Nevertheless, the DAMS model can still be applied to large-scale cases because:

(1) The computational time shown in Fig. 12 is based on a personal computer with a limited computational and storage capacity. Since the different replications are independent, if we employ distributed/parallel computing techniques, the computational time will reduce linearly to the computational capacity. For example, in case of $n = 225$, if we employ a work station with 50 cores (not very high requirement), then the computational time will be around 4.18 hours.
(2) According to the Law of Moore, the computational capacity of computers will double every 24 months.[51] The last 50 years show the correctness of Moore's Law; however, the number of tanks in the chemical and process industries will not increase so quickly.
(3) The proposed model can be used to explore possible scenarios, without knowing the probabilities, which otherwise would be very difficult if done by a human. In this case, it is not necessary to run the model so many times (see Appendix C). For example, if we just run the model 5,000 times (thus the computational time will be 1/200 of the time given in Fig. 12), then a 99.3% reliability can be reached that any notable scenario (i.e., those with a probability higher than 0.001) will be recorded.

6. DISCUSSION

The three case studies implemented in Sections 4 and 5 demonstrated that the DAMS model

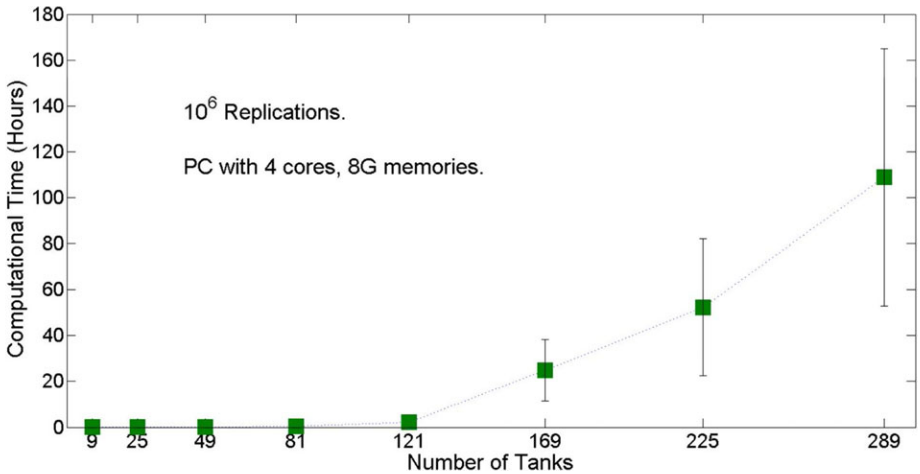

Fig. 12. Results of computational time analysis.

is reliable in terms of the correctness of probabilistic, the advantages of capturing the time dimension, and the extensibility to large-scale cases. Figs. 8 and 9 demonstrate that DAMS correctly gets the probabilistic assessment of domino effects, taking into consideration of higher-level domino effects (see, e.g., scenarios 6, 10, and 13) and synergistic effects (see, e.g., scenario 10). Fig. 11 illustrates how the time dimension of domino effect could change the risks, which, however, is one of the main achievements of the developed model. Fig. 12 shows the capability of the model of calculating domino risks of plants containing hundreds of tanks, whereas the current existing models are only able to deal with dozens of tanks.

Compared to the case studies, the realistic situation in industrial practice is more complicated, mainly due to three reasons: (i) the variety of domino agents (e.g. tanks, pipeline, mobile vehicles, etc.); (ii) the variety of accident scenarios (e.g., jet fire, VCE, etc.); and (iii) the number of domino agents.

To deal with the variety of domino effects, we proposed the tank agent model, which with different static attributes can describe most kinds of tanks in a typical chemical and process industry (for instance, different shape attributes can describe different geometries, and then in the dynamic model, different types of tanks will use different parameters in the Vulnerability Model). For pipelines and mobile vehicles as well as some other kinds of domino agents, we need to develop agent-specific models. However, these models can be built in a similar way to the tank agent model.

To deal with the variety of accident scenarios, we only considered heat radiation escalation to represent pool fires, jet fires, etc. In order to take other escalation vectors such as overpressure escalation and fragments into consideration, more chemical-related domain knowledge is needed, and thus stronger cooperation between simulation experts and chemical engineering experts.

To address the number of domino agents, we propose the "tank agent model," which is the basic unit in a domino effect; thus, regardless of the number of tanks, each physical tank is represented as a tank agent. In fact, the model proposed in this study has two important properties: (i) the tank agent's static and dynamic model will not be influenced by the number of tanks; and (ii) the necessary replications of computational experiments will not be influenced by the number of tanks (see Appendix C).

To address the first and second reason, new models are needed, though they can be developed analogously. The model proposed in this study can be used in case of an increasing number of domino agents (i.e., the third reason).

7. CONCLUSION

In this work, an agent-based modeling and simulation approach is proposed to estimate the potential domino risks in chemical plants. Tanks are modeled as agents that receive heat radiation from the tanks already on fire, run state transformation based on the received heat radiation, and if get on fire broadcast heat radiation to other tanks. The environment is modeled as an observer to manage global information. The proposed approach is able to capture not only the probabilistic dimension of domino effect, but also the time dimension, which describes the timing when the domino effect may happen. Higher-level domino effects, as well as synergistic effects, are also considered. The correctness, the advantages, and the extensibility of the model are illustrated by the computational experiments carried out on several case studies.

This work is a first attempt to employ an agent-based modeling and simulation (ABMS) approach to do domino risk assessment in chemical plants. By successfully modeling the dynamic procedure of domino effects, the outcome of this research can be used to support optimal and dynamic allocation of emergency resources. Furthermore, by tagging initial events on multiple targets, the model can support domino effect assessment triggered by a number of simultaneously failed tanks, a situation that may occur in case of a terrorist attack.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Appendix A
Appendix B
Appendix C
Appendix D