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Applying Agent Based Modelling and Simulation for Domino Effect Assessment in the Chemical Industries

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The propagation of accidents among process units may cause amplification of accident magnitude, resulting in a domino effect chain. Several catastrophic accidents occurred in the process and chemical industry presented these features. Hence, research efforts have been given to the analysis of the domino effects in order to enhance prevention and mitigation strategies. In this work, challenges of analysing domino effects in the chemical industries are discussed, highlighting that quantitative analytic approaches suffer from the complexity on assessing domino effects, especially when dealing with simultaneous accidents propagating among multiple units. Therefore, a bottom-up modelling approach, namely, the agent based modelling and simulation (ABM&S) approach, is introduced for analysing domino effects. Moreover, a prototype model for assessing domino effects in the chemical industries by using agent based modelling and simulation (DAMS) is given and further extensions of the prototype model is also discussed, highlighting the potential benefits.

1. Introduction

Studies of past chemical disasters, such as the explosion in Buncefield 2005, the explosion in Corbin 2003 etc. reveal that domino effects played a role in increasing the consequences of these disasters (Reniers and Cozzani, 2013). Chemical sites sometimes have to store/transport/process hazardous (e.g., flammable/toxic/explosive) substances in extreme operative conditions (e.g., high pressure, low temperature). Therefore, loss of containment in a single unit may generate accidents of sufficient severity able to affect neighbour installations, thus forming the domino chain. The existence of domino effects makes assets in a chemical site dependent to each other, resulting in systemic risk.

When analysing the domino effect chain, the failure evaluation of a single unit or target is already a complex task, involving the assessment of the target response to the escalation vector: overpressure (Cozzani and Salzano, 2004), fragment damage (Tugnoli et al., 2014) or heat radiation caused by fire, inducing the pressure build-up (Landucci et al., 2013). The complexity is increasing when dealing with the analysis of the domino propagation among multiple units. Therefore, several research efforts were devoted to the analysis of domino effect propagation chain, but mostly adopting simplified and analytic approaches (Reniers and Cozzani, 2013). The present work is aimed at providing a critical analysis of the currently applied tools for the domino effect propagation assessment, highlighting challenges and criticalities (Section 2). An alternative innovative approach, namely the agent based modelling and simulation (ABM&S), is suggested in Section 3 to analyse domino effects, thus overcoming the limitation of the currently adopted research approaches. Indications for future research on the use of ABM&S for domino effects analysis are suggested in Section 4 and, finally, conclusions are given in Section 5.

2. Challenges on assessing domino effects in the chemical industries

Relevant elements of complexity affect the analysis of the domino effect in the framework of chemical industries.

Firstly, process units involved in the domino effect chains may fail resulting in multiple possible scenarios, such as pool fire, explosion, fireball, etc. Moreover, different escalation vectors (i.e., different domino propagation mode) are associated with each possible primary scenario. Table 1 illustrates some primary scenarios and their corresponding escalation vector.

Secondarily, the domino propagation analysis is often involving probabilistic and, thus not only deterministic evaluations, with the need of specific tool for the estimation of equipment vulnerability. For example, a storage unit affected by fire features a probability of being damaged by the heat up (Landucci et al., 2013).

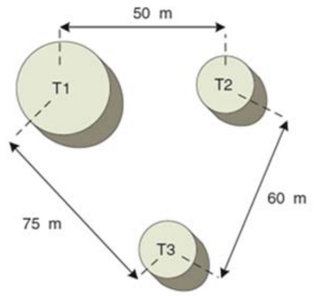
Thirdly, synergistic effect interconnects different escalation vectors between different installations. Due to the existence of synergistic effect, either a single unit resulting or not in a fire would affect the damage probability of other units and in a setting of n total equipment, there would be approximately 2^n possible domino chains.

Table 1. Failure scenarios and their corresponding escalation vectors. Adapted from (Reniers and Cozzani, 2013)

Primary Scenario	Escalation Vector
Pool fire	Radiation, fire impingement
Jet fire	Radiation, fire impingement
Fireball	Radiation, fire impingement
Flash fire	Fire impingement
Mechanical explosion	Fragment projection, overpressure
Confined explosion	Fragment projection, overpressure
BLEVE	Fragment projection, overpressure
VCE	Overpressure, fire impingement

BLEVE: boiling liquid expanding vapor explosion; VCE: vapor cloud explosion

An example would be useful to further explain the abovementioned complexities of the domino effects in the chemical industries. Figure 1 shows a layout of three atmospheric tanks storing flammable liquids. Figure 2 shows the possible domino propagation chains under the condition that an initial event is happened on tank 'T1'. For simplicity reason, only one scenario, i.e. pool fire, is associated with each of the three tanks.



Tank ID	Diameter (m)	Height(m)	Substance
T1	20	10	Hexane
T2	14	8	Benzene
T3	14	8	Benzene

Figure 1. Layout and features of process units adopted for an illustrative case study.

In Figure 2, the left-hand side blocks demonstrate the time line and the events that may happen, while the right-hand side is an event tree illustrating the domino evolution. ttf_{target}^{source} denotes the time to failure when the target tank receives heat radiation from the source tank. In particular, $ttf_2^1$and ttf_3^1 represent the time to failure of tank T2 and T3 when exposed to the primary pool fire generated by the failure of tank T1. t_r^2 represents the time to failure of tank 'T3' when it receives heat radiation from both 'T1' and 'T2' (i.e., synergistic effects). pf_{target}^{source} denotes the probability of being damaged of the target tank when it receives heat radiation from the source tank (s). p_{i1} and p_{i2} are the ignition probabilities of the liquid spilled from primary and secondary tanks, respectively.

In the simplified example (only three tanks and only the pool fire is considered), finally 13 possible domino propagation results are obtained. For instance, the result s1 (shown as red colour in the event tree) represents the domino effect chain as: at time 0, 'T1' catches fire, at time ttf_2^1, 'T2' catches fire, and at time 't_r^2', 'T3' catches fire. In a realistic setting featuring hundreds of units and multiple failure scenarios may happen, the analysis would be super complex.

However, if the modeller only concerns indicators such as which installation would fail at what time and ignores the intermediate steps of the domino chain, then those possible domino chains (i.e., the 13 results) can be categorized. For instance, in the example, although there are 13 possible results, tank 'T2' would only have 3 possible results. The three nodes in the bottom of Figure 2 represent the three results of tank 'T2': R1 - Tank 'T2' catches fire at time ttf_2^1; R2 – Tank 'T2' catches fire at time ttf_3^1; and R3 – Tank 'T2' does not catch fire.

In conclusion, due to the facts that 1) installations may have multiples failure scenarios; 2) a domino propagation is a probabilistic procedure; and 3) synergistic effect exists, the event tree for analyzing domino effects would have enormous branches if there are dozens of tanks. Furthermore, these branches could finally be categorized according to some indicators.

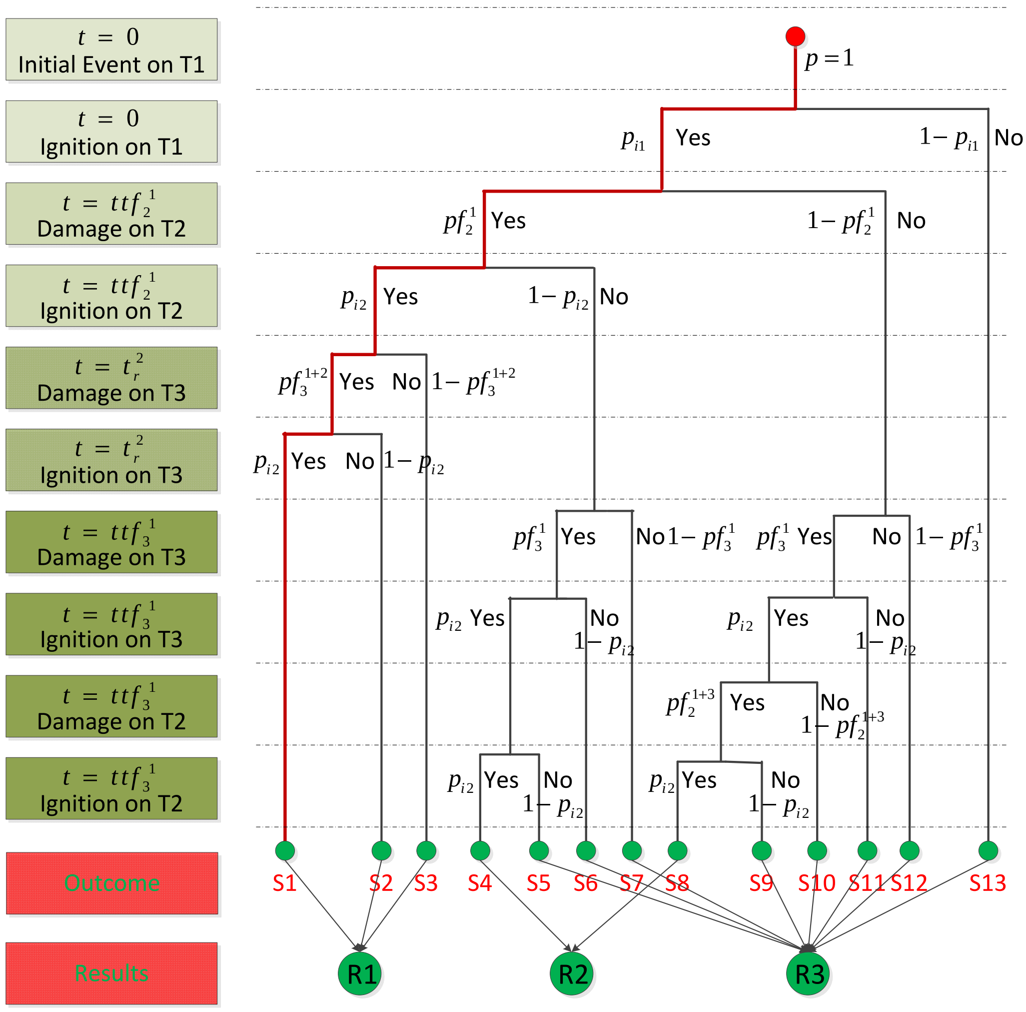


Figure 2. Possible domino propagation procedure of the three tanks example

A straightforward idea is to cut branches in the early stage of plotting the event tree. However, the first obstacle of doing so is the difficulty of defining cutting criteria. Furthermore, if the criteria of cutting branches that has a small probability would be used, then most of the branches might be cut since there are enormous branches and each branch would have a quite small probability. Moreover, if a set of branches that although each has a small probability but belong to the same category, and if this set of branches would be cut, then the probability of the category would be dramatically affected. For instance, in Figure 2, the probabilities of branches s9 to s13 may be small, and if they are cut, then the probability of R3 would be dramatically reduced.

The propagation of domino effects in the chemical industries is a complex phenomenon. Analytic approaches (e.g., event tree (Landucci et al. (2015), Bayesian Network (Khakzad et al. (2013) etc.) aim to study the phenomenon from a system level and these methods, if applied to a case study with dozens of installations, would not be able to handle the complexity. Monte Carlo Simulation (MCS) has also been introduced for the domino effect assessment (Abdolhamidzadeh et al. (2010)), being able handle the complexity of the procedure, but failed on capturing the dynamic evolution of domino effects.
However, a domino effect is a chain of the involved installations' behaviors and each installation actually has very simple behaviors. If research concentration would be shifted from the domino chain (system level phenomenon) to the behaviors of each unit (micro level rules), an ABM&S approach would be applied.

3. A bottom-up approach for assessing domino effects: agent based modelling and simulation (ABM&S)

3.1 ABM&S Brief

Agent based modelling and simulation (ABM&S) is a bottom-up approach of studying complex systems (Macal and North (2010)). Instead of studying a complex system from a macro level, for instance, by analyzing system behavior, or, by studying patterns and structures of the system, ABM&S focuses on the micro level of the system, by studying the basic components that form the system. With proper models of the basic components, system behaviors would emerge (Holland (2000)).

3.2 ABM&S for domino effect analysis

In an early research, Zhang et al. (2017) proposed a model for assessing Domino effects by using ABM&S (DAMS). The DAMS model consists of an environment model and a set of tank agents. The environment model stores all the global information such as information of the site (e.g., number of tanks, layout of the tanks, heat radiation information etc.) and weather information. The tank agent models the installations that involve in the domino propagation procedure.

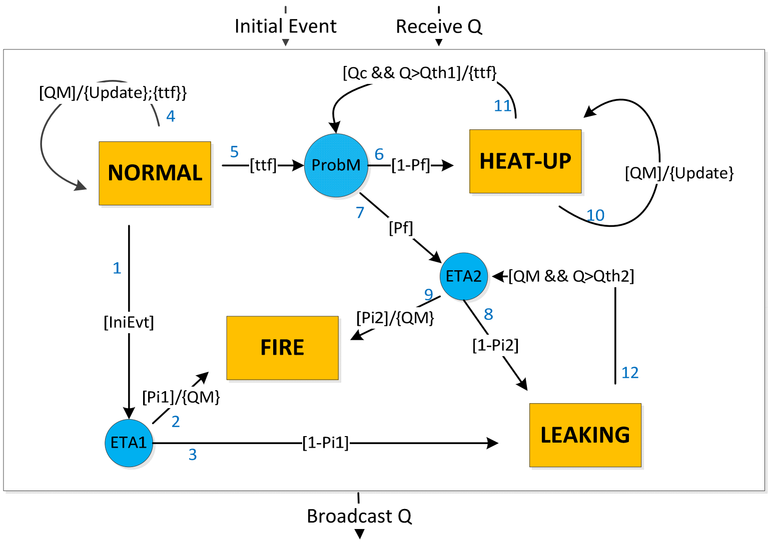


Figure 3. Behaviour model of the tank agent, adapted from (Zhang et al., 2017)

Figure 3 shows the tank agent's dynamic behavior model in a domino effect trigged by pool fire, and it is developed only for atmospheric tanks. However, the approach can be extended to any other failure scenario and equipment type. First of all, the tank agent reacts to an initial event (thus to be a primary tank in the domino chain) or receives heat radiation from other tanks (i.e., being affected by tanks on fire). In case the tank agent also results in a fire scenario, it will broadcast heat radiation to all other tanks. The state chart in the block denotes the tank agents' inner state transfer. Four states are defined for the tank agent, namely, Normal state, Heat-up state, Leaking state, and Fire state.
A tank stays in Normal state if there is nothing happening. If there is an initial event happens to the tank and the tank content is ignited (i.e., arrows 1 and 2), then the tank results in a fire and becomes the primary tank for the domino chain. If an initial event happens to a tank but no ignition occurs, the tank will be releasing the content without fire. If the primary tank content catches fire, it broadcasts heat radiation to all other tanks, and

therefore other tanks will receive this heat radiation. After receiving a heat radiation, the model calculates the ttf, thus the time to reach failure conditions (i.e., arrow 4). In this step, simplified correlations for ttf calculation as a function of heat radiation intensity may be adopted (Landucci et al., 2013).
When time comes to the ttf, the tank calculates the probability of being damaged by employing a vulnerability model. For this purpose, in (Zhang et al., 2017) a probit model was adopted (Landucci et al., 2009) (i.e., arrow 5). If the tank is damaged (i.e., arrow 7), and if the tank content is ignited (arrow 9), it results in a fire (thus being a follow-up node in the domino chain), while if there is no ignition (arrow 10), the tank is just damaged and the stored substance would leak to the basin. If the tank is not damaged (arrow 6), it is only heated up. It is noteworthy that before being damaged, a tank may receive heat radiation from multiple sources (i.e., synergistic effects), and this is descripted by arrows 4, 10, and 11. Arrow 12 means that a damaged tank still has a probability of resulting in a fire, due to subsequent ignition caused by subsequent fires in the domino scenario evolution.
In DAMS, research focuses on modelling the involved units' behaviors instead of focusing on analyzing the domino chain. If the basic components (i.e., agents) are well modelled, by running simulations the system phenomenon (i.e., the domino effects) would emerge.
It is worth noting that one simulation of the DAMS model only represents one possible evolution of the domino effect. As mentioned in Section 2, one challenge of assessing domino effects is that it is a probabilistic chain instead of a deterministic chain. Therefore, with the support of the DAMS, Monte Carlo Simulation (MCS) (Zio (2013)) are needed, to get the statistical result of the domino effect.

4. Discussion

The research of employing ABM&S for the domino effects assessment is still in its early stage. The DAMS model presented in (Zhang et al., 2017) are restricted to example applications, in particular considering one type of equipment (e.g., atmospheric vertical cylindrical tanks) with one possible final outcome, i.e., pool fire. However, the key innovation of using ABM&S is the paradigm shift to a bottom-up approach. Future researches can be done from several aspects described in the following.

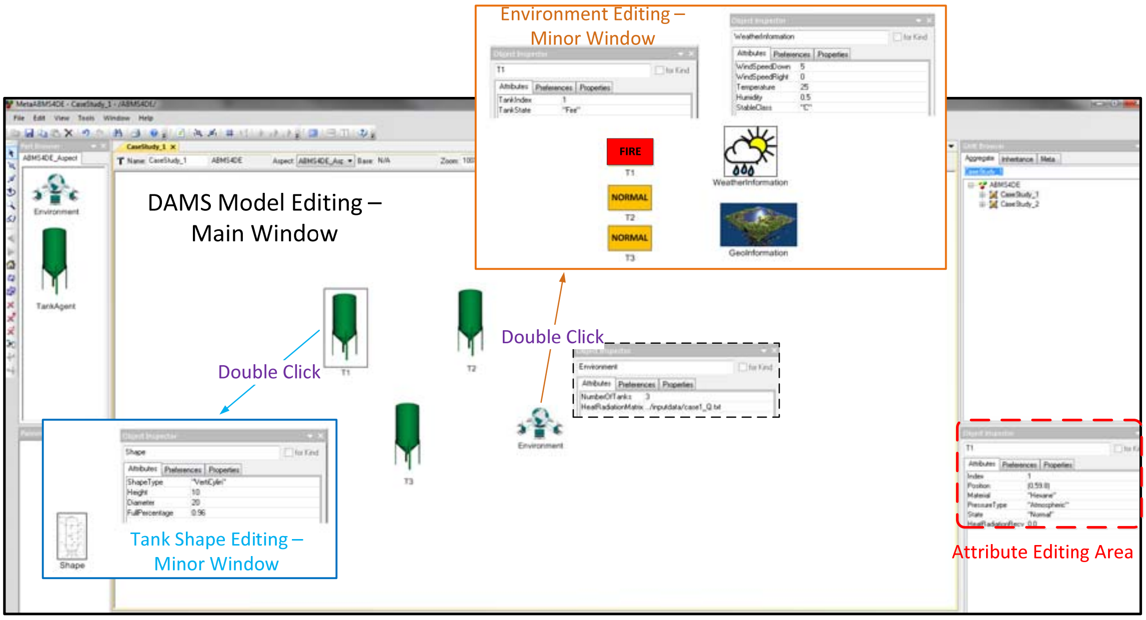


Figure 4. A configurable interface for the DAMS model

Defining installation agent also for other equipment, e.g. pressurized tanks, cryogenic vessels, utilities, etc. and taking into more failure modes into consideration, is one of the promising research directions. To do so, more domain knowledge is needed: analyzing the possible response of the different unit types in the domino chain; introducing more final outcomes (e.g. expand to other fire and explosion scenarios); and investigating the possible effects of a given failure mode for one piece of equipment on the other units.
Integrating safety barriers into the DAMS model is another promising research direction. Among others, Landucci et al. (2016) studied the performance of different types of safety barriers in a domino effect triggered by fire. Safety barriers are actually also working on individual equipment, for instance, by cooling down a

pressurized tank (Water Deluge System). Therefore, the DAMS model can also be applied to estimate the performance of safety barriers.

Developing a user-friendly interface for the DAMS model is also an interesting work. Figure 4 shows a prototype of the interface (the GME software (Davis (2003)) is used) and the three tanks example of Figure 1 is modelled. On the left-hand column, the defined models (i.e., environment model and tank agent at this stage, while in the future it may also have some other models) are shown. Users can drag the models from the left-hand column to the main window. The user may also edit the models in the main window. After deploying the model, the use may run the model by simply clicking a button. Furthermore, result analysis function can also be integrated to the interface.

5. Conclusion

Domino effect in the chemical industries is a complex phenomenon, due to the various failure modes of the involved installations, the probabilistic propagation of the domino chain, and the existence of the synergistic effects. Conventional analytic approaches aim at analyzing the domino effect from a macro level, suffering from the complexity of the analysis procedure.

Agent based modelling and simulation (ABM&S) has been proposed as a promising approach for modelling complex system and introduced in this work for assessing domino effects in the chemical industries.

The proposed DAMS model focuses on the micro behaviours of installations, being more precise (i.e., less simplified) and being able to capture dynamic evolutions of the domino effect. In the DAMS model, installations are not just a node (as in the Bayesian network methodology), but an individual that has its own behaviour rules. Domino effects in the DAMS model is an emergence phenomenon of the dynamic interactions among installations, thus the time dimension of the propagation of domino effects is naturally involved. However, the research of employing ABM&S for assessing domino effects in the process industry has just started and the current DAMS model is still in its weak form. More research efforts as discussed in Section 4 are needed to enhance the model.

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