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Using graph theory to analyze the vulnerability of process plants in the context of cascading effects

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ABSTRACT

Dealing with large quantities of flammable and explosive materials, usually at high-pressure high-temperature conditions, makes process plants very vulnerable to cascading effects compared with other infrastructures. The combination of the extremely low frequency of cascading effects and the high complexity and interdependencies of process plants makes risk assessment and vulnerability analysis of process plants very challenging in the context of such events. In the present study, cascading effects were represented as a directed graph; accordingly, the efficacy of a set of graph metrics and measurements was examined in both unit and plant-wide vulnerability analysis of process plants. We demonstrated that vertex-level closeness and betweenness can be used in the unit vulnerability analysis of process plants for the identification of critical units within a process plant. Furthermore, the graph-level closeness metric can be used in the plant-wide vulnerability analysis for the identification of the most vulnerable plant layout with respect to the escalation of cascading effects. Furthermore, the results from the application of the graph metrics have been verified using a Bayesian network methodology.
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1. Introduction

Process plants are normally characterized by a number of dependent and interlinked components which contain, carry, or process hazardous (e.g., flammable, explosive, toxic) materials usually in high-temperature high-pressure conditions. As a result, an otherwise ordinary accident or undesired event which could be tolerated or controlled in other industrial plants has the potential of turning into a catastrophe within a few hours due to the possibility of triggering a cascading effect. Cascading effects (also known as domino effects or chains of accidents) in the process industry are low-frequency high-consequence chains of accidents. In case of a cascading effect, a primary accident (e.g., a fire) in a primary unit (e.g., a storage tank) propagates to neighboring units and triggers secondary accidents in the vicinity of the primary unit and so forth. To consider it a cascading effect, the overall consequences of such a sequence of accidents should be higher than those of the primary event [1]. Usually, the final outcome of a cascading effect is several orders of magnitude more severe than that of the primary accident.

The propagation of the primary accident is usually carried out by means of escalation vectors such as fire impingement, fire engulfment or heat radiation in the case of fires, and overpressure wave or projectile fragments in the case of explosions. These escalation vectors help the primary accident to propagate by causing damage (loss of containment or loss of physical integrity) to adjacent units (target units). The probability of escalation, however, depends on a variety of factors such as the type of the primary accident and the intensity of escalation vectors, the distance between the primary unit and the target units, the vulnerability of the target units, and the type and inventory of chemical substances involved [2].

In spite of their extremely low frequency, the possibility of cascading effects should not be ignored in safety risk assessment and vulnerability analysis of process plants. In fact, high complexity and interdependencies within process plants make them increasingly vulnerable to cascading effects. For instance, LPG[2]-induced cascading effects in Mexico City in November 1984 left 650 deaths and 6500 injuries and destructed three process plants. Most recently, in December 2005, a series of fires and explosions in an oil storage plant in the Buncefield Complex, in the United Kingdom, led to the largest fire in peacetime Europe, leaving 43 injuries and causing huge devastation in the area [3]. Cascading effects have long been recognized in process

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plants and chemical infrastructures [4–7], and have been studied in risk assessment and management of process plants over the past decade [8–21].

In the context of safety risk assessment and management of critical infrastructures, however, other factors such as vulnerability, robustness, and resilience should also be taken into account [16,23,24]. Johansson et al. [24] use the term vulnerability "as the inability of a system to withstand strains and the effects of failures". In the present study, however, vulnerability is defined as the capability of a unit or process plant to foster either the onset or the escalation of potential cascading effects. On the contrary, robustness can be defined as the ability of the process plant to hamper the escalation of cascading effects. As a result, vulnerability and robustness can be regarded as two complementary terms in this context. It is also worth noting that the concept of vulnerability used in the present study should not be mistaken for the common term of vulnerability analysis in cascading effects where the damage probability of a target unit due to the escalation vectors of a primary accident is usually calculated using vulnerability functions [8]. While the aim of traditional risk analysis is to identify hazardous events, their likelihood and potential consequences, the aim of vulnerability analysis is to explore the system weaknesses by identifying those critical components whose failure can adversely affect the performance of the system. Compared with risk analysis, in vulnerability analysis, however, the failure probabilities are less important and more emphasis is given to the extent and severity of the consequences [25]. Furthermore, vulnerability analysis is usually performed using deterministic or analytical techniques – as opposed to probabilistic methods used in risk analysis – to seek the impact of accidental or intentional failures on the performance of a system [16,23].

Vulnerability analysis can be considered from two perspectives: (i) plant vulnerability and (ii) unit vulnerability. Plant vulnerability can be interpreted as an inherent characteristic of a process plant to measure how far and to what extent the adverse effects of a primary accident can propagate through the plant. This interpretation of vulnerability can be beneficial when deciding among alternative layouts in the early design stage of process plants so that the most robust layout could be selected. Unit vulnerability analysis, however, can be carried out to identify critical units within a process plant. This interpretation of vulnerability can be employed to allocate proactive countermeasures to the weak points and critical units so that the onset of cascading effects can be prevented or their escalation can be hampered. Generally speaking, in a chain of accidents which starts from unit A, traverses unit B, and terminates at unit C (i.e., $A \rightarrow B \rightarrow C$), A, B, and C are known as source, intermediate, and sink or terminal units, respectively [16]. In a process plant, a critical component can be deemed as either (i) a source unit whose failure would cause large adverse consequences to the plant (critical initiating unit) or (ii) an intermediate unit whose failure helps escalate a previously occurred accident through the plant to a large extent (critical transmitting unit) or (iii) a unit which turn outs to be the sink unit in many potential cascading effects with different sequences of source and intermediate units within a process plant (critical terminal unit).

Compared to well-established methods available in risk analysis of cascading effects, relevant work in the field of vulnerability analysis has been very few [16,20–22,26–28]. Cozzani et al. [26] introduced a set of domino indices to score and identify critical units within process plants with respect to escalation events. Khakzad et al. [20] established a Bayesian network methodology to identify the most probable sequence of accidents (i.e., $\max_{A,B,C} P(A \rightarrow B \rightarrow C)$) in a process plant. Most recently, Reniers and Audenaert [16] used a network theory to rank most vulnerable intermediate and terminal units based on "terminal and propagation vulnerability indices". Similar work has been conducted to determine safety distances and safety inventories [21,27] in order to reduce the vulnerability of process plants subject to cascading effects. Representing a process plant by means of nodes (units of the plant) and edges (escalation vectors among the units) of a graph in this study, we aim to explore the applicability and efficiency of a set of graph metrics to both unit and plant vulnerability analysis of process plants, and chemical infrastructures in general, in the context of cascading effects.

This paper is organized as follows. The basic concepts and escalation mechanism of cascading effects within process plants are recapitulated in Section 2. The graph theory metrics used in this work are introduced and briefly explained in Section 3. A brief description of Bayesian networks and its application to modeling cascading effects [20] is replicated in Section 4. In Section 5, we apply graph metrics to vulnerability analysis of hypothetical process plants in order to identify most critical initiating and transmitting units within a plant (unit vulnerability analysis) and also to rank different plant layouts in terms of vulnerability (plant vulnerability analysis), and then compare the results obtained from the application of graph metrics with those from the Bayesian network methodology. The main conclusions drawn from this work have been presented in Section 6.

2. Terminology and escalation mechanism of cascading effects

Cascading effects take place when an accident in a unit (primary unit) propagates to other units (secondary units) by means of escalation vectors. Escalation vectors are physical effects such as fire impingement, fire engulfment, or heat radiation in the case of a fire, and deflagration overpressure or projectile fragments in the case of an explosion. Simple methods for calculation of escalation vectors can be found in [29–31]. The probability of escalation, however, depends not only on the type and intensity of escalation vectors but also on the inventory of chemicals and the vulnerability of target units. Moreover, to determine if a target unit is likely to be impacted by an escalation vector, the intensity of the escalation vector at the point of interest (i.e., the location of the target unit) should be higher than a corresponding threshold value[3]. For example, for atmospheric vessels (e.g., atmospheric storage tanks) the threshold values for the heat radiation and the overpressure have been proposed as $Q_{th} = 15$ kw/m^2 and $P_{th} = 22$ kPa, respectively [26].

Fig. 1 shows the onset of a cascading effect in which a fire (primary accident) in the unit X1 (primary unit) is likely to impact the neighboring units X2 and X3 but not X4. The reason is the intensity of the escalation vectors (here heat radiation) received by X2 (Q_{12}) and X3 (Q_{13}) is above the threshold value (i.e., $Q_{12} = Q_{13} = 20$ kW/m^2 $> Q_{th} = 15$ kW/m^2), while that of X4 (Q_{14}) is not (i.e., $Q_{14} = 8$ kW/m^2 $< Q_{th} = 15$ kW/m^2). Therefore, X2 and X3 could be selected as potential secondary units involved in the cascading effect, helping to escalate the cascading effect to the first level[4]. After either X2 or X3 is involved in the cascading effect, it can contribute with X1 to impact X4 to escalate the cascading effect to the second level only if the superposition of the respective escalation vectors is greater than the corresponding threshold value, which is the case for the cascading effect shown in Fig. 1 (i.e., $Q_{14} + Q_{24} + Q_{34} = 28$ kW/m^2 $> Q_{th} = 15$ kW/m^2). This contribution of units (the primary and secondary units) to impact another unit (tertiary unit) is known as the synergistic effect.

[3] If the intensity of the escalation vector is below a threshold value, the likelihood of escalation would be practically negligible.

[4] The primary accident in X1 is considered as a zero-level cascading effect since a chain of accidents has not yet formed.

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