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A decision model to allocate protective safety barriers and mitigate domino effects

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ABSTRACT

In this paper, we present a model to support decision-makers about where to locate safety barriers and mitigate the consequences of an accident triggering domino effects.

Based on the features of an industrial area that may be affected by domino accidents, and knowing the characteristics of the safety barriers that can be installed to stall the fire propagation between installations, the decision model can help practitioners in their decision-making. The model can be effectively used to decide how to allocate a limited budget in terms of safety barriers. The goal is to maximize the time-to-failure of a chemical installation ensuring a worst case scenario approach.

The model is mathematically stated and a flexible and effective solution approach, based on metaheuristics, is developed and tested on an illustrative case study representing a tank storage area of a chemical company. We show that a myopic optimization approach, which does not take into account knock-on effects possibly triggered by an accident, can lead to a distribution of safety barriers that are not effective in mitigating the consequences of a domino accident. Moreover, the optimal allocation of safety barriers, when domino effects are considered, may depend on the so-called cardinality of the domino effects.

1. Introduction

Cascade events or domino effects truly are a timely topic. Domino effects can be defined as accidents in which a primary unwanted event propagates within a system (“temporally”), or/and to nearby systems (“spatially”), sequentially or simultaneously, triggering one or more secondary unwanted events, in turn possibly triggering further (higher order) unwanted events, resulting in overall consequences more severe than those of the primary event [1]. In this paper cascade events and domino effects are treated as synonyms even if the former are mainly used in works related to social and organizational effects/accidents, while the latter are generally mentioned in technical studies. We live in a time where there is ever more industrial activity, especially within the chemical and process industry. This translates into a non-stop increase in amounts of hazardous materials being processed, stored, transported, etc. between chemical industrial parks worldwide. As a matter of fact, the need for more industrial activity is driven by the observation that population figures have been sharply increasing on a global scale since a century. Irrespective of the underlying reasons of both facts, taking the combination of both these facts into consideration, automatically leads to the question about their combined impact on societal risk and safety. In the chemical industry, an important aspect of this impact can be summarized by the potential of escalation of an industrial accident to a major disaster, or a so-called domino effect.

Although such events are less known than well-recognized major accidents such as for example vapor cloud explosions (VCEs), BLEVEs, and the alike, they may have even more disastrous consequences compared to those better known accidents [2]. They are less recognized and studied by industry, academia and regulators due to the fact that their likelihood is even much lower than that of the better known major accident scenarios. Nonetheless, since they became an issue in the Seveso II Directive in 1996, and also because domino accidents do happen on a worldwide scale (even if they are extremely rare), ever more research is carried out by academics and industrials to further advance our knowledge on these obscure events.

Several lines of research have been initiated with respect to the domino effect topic. For example, indices have been suggested by Tugnoli et al. [3] and Reniers and Audenaert [4]. Tugnoli et al. [3] developed an index to assess the domino potential hazard including the effect of inherent and passive protection measures. Reniers

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and Audenaer [4] elaborated an index to rank chemical installations within any industrial area, and based on a their vulnerability for domino effects. Nguyen et al. [5] analyzed the potential for domino effects produced by projectiles generated by explosions in industrial facilities. Salzano et al. [6] investigated domino effects related to home-made explosives. Landucci et al. [7] elaborated a quantitative risk assessment where domino effects are taken into account, and where events are triggered by fire. The model is based on an estimation of vessel time to failure. Cozzani et al. [8] studied inherent safety approaches providing the possibility to prevent knock-on events. Khakzad et al. [9] proposed an approach to analyse domino effects by using Bayesian networks. Reniers [10] looked into the problem of cross-plant collaboration and the lack of sufficient information exchange to optimize protection against domino effects, employing game-theoretical modeling to do so. Darbra et al. [11] analyzed 225 domino incidents during hazmat transportation. Reniers et al. [12] investigated the possibility of attenuation-based security within chemical industrial areas. Furthermore, in 2013, Reniers and Cozzani [13] edited a comprehensive volume on the modeling, prevention and management of domino effects in the process industries, providing the state-of-the-art at publication date and indicating the leeway for further exploration of the domino effects research area. As can be seen from this brief overview of important past research on domino effects, the subject is looked at from a safety as well as from a security point of view, and research efforts are ever more intensifying.

A lot of research is concerned with design-based safety with respect to domino effects, and hence, researchers mainly focus on managing domino effects in an inherent way. This is, of course, the most optimal way to deal with such potentially devastating events. However, this is not always possible. If installations (for example storage tanks) are present in a certain industrial setting, it is not easy to just replace them or to make major design-based (e.g. lay-out) changes. Therefore, it is also very important that research is aimed at optimizing add-on safety with respect to domino effects. The study explained and discussed in this paper is aimed at such optimization of safety barriers within existing industrial settings, and employs operational research techniques and science to do so.

The concept of *barrier* is widely used to denote some form of obstruction towards an emerging threat or accident [14]. Different terms (barrier, defence, protection layer, safety critical elements, safety function, etc.) are used in the literature to describe barriers as risk reducing measures (the reader is referred to [15] for more details). Even though there does not exist neither a universally accepted definition of safety barriers nor any agreement regarding their effects, some common features (e.g. barrier systems, barrier functions, safety elements) can be found in the literature [16]. In order to overcome this issue, the Norwegian Petroleum Safety Authority outlined specific definitions for safety barriers, safety functions, safety elements. In particular barriers are defined as "…technical, operational and organizational elements on an offshore or onshore facility, that, individually or collectively, reduce the possibility of concrete failures, hazard and accident situations occurring, or that limit or prevent harm/inconveniences". Moreover, barriers are intended either to prevent a concrete chain of events from occurring or to affect a chain of events in a way that limits harm and/or losses. Barriers fulfil their functions in case of failures, hazard and accident situations on an offshore or onshore facility, be it a case of potential harm done to people, the external environment and/or financial assets [17]. In the remainder of this paper, we will refer to safety barriers having in mind the concepts provided by the Norwegian Petroleum Safety Authority.

The evolution of domino accidents, triggered by heat radiation, overpressure effects, or missile projection, depends on the presence (or absence) and the performance of safety barriers. Safety barriers may have the potential to prevent escalation, for example, in case of heat radiation, delaying or avoiding the heat-up of secondary targets. Thus, safety barriers play a crucial role in domino effect prevention and mitigation within existing industrial settings. More specifically, add-on safety barriers can indeed: (i) restrict the propagation of domino effects; (ii) mitigate the consequences of domino effect; and (iii) be extremely important in terms of increasing the time to failure of chemical installations.

At present, in industrial practice, the decision to take certain safety barriers for dealing with major accident scenarios does not take domino effects of a higher order into account. At most, possible direct escalation of major accident scenarios is considered (thus only possible domino events with cardinality 0, see Section 2). However, this is a myopic way of tackling domino effects within chemical parks. Especially with respect to security issues, this myopic approach may prove to be largely insufficient. Therefore, to optimize current practice, there is a need for studying in what way higher order domino events can be taken into account in the decision-making process of investing in add-on safety barriers for existing industrial areas. Possibly, considering higher-order domino events in the safety barrier investment problem will lead to alternative decisions. Hence, an approach and a computer program to determine the most optimal safety barrier investment decision for dealing with domino effects in existing industrial settings, and thereby considering higher-order domino events, is currently non-existent in academic literature and lacking in industrial practice.

The remainder of the paper is organized as follows. In Section 2 the decisional model and its mathematical representation is presented. In Section 3 an effective solution algorithm based on a metaheuristic approach is developed. This solution method is tuned and tested on a realistic study case in Section 4. Section 5 concludes the paper and presents some suggestions for future research.

2. Problem description

In this section, the problem is described and mathematically stated. The main objective of the model is to support decision makers to optimally locate protective barriers within an industrial setting of chemical installations, to mitigate domino effects. Given a budget constraint, the optimal mix of protective barriers needs to be selected in order to delay the propagation of a major fire resulting from accident towards a chemical installation that might further trigger the failure of other chemical installations engendering thus escalation effects.

Depending on the intensity of the domino effects, the cardinality D can be used to denote how many domino events happen after the initiating failure/accident. We suppose that the initiating event always happens at a root installation and from it fire might propagate to neighboring installations engendering thus a cascade effect.

In particular, domino events characterized with cardinality 0 represent the first cascade effect as a consequence e.g. of an accident to a chemical installation (the so-called "primary domino events"), whereas cardinality 1 refers to secondary domino events, cardinality 2 to tertiary domino events and so on [18]. It is worth noticing that when cardinality is equal to zero the first domino effect is produced. Using this taxonomy, it is possible to classify domino effects triggered by installation i and affecting:

(i) *Situation I*: A single neighbor installation j by means of fire propagating from i to j (in case $D=0$).