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An external domino effects investment approach to improve cross-plant safety within chemical clusters

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ABSTRACT

Every company situated within a chemical cluster faces the risk of being struck by an escalating accident at one of its neighbouring plants (the so-called external domino effect risks). These cross-plant risks can be reduced or eliminated if neighbouring companies are willing to invest in systems and measures to prevent them. However, since reducing such multi-plant risks does not lead to direct economic benefits, enterprises tend to be reluctant to invest more than needed for meeting minimal legal requirements and they tend to invest without collaborating. The suggested approach in this article indicates what information is required to evaluate the available investment options in external domino effects prevention. To this end, game theory is used as a promising scientific technique to investigate the decision-making process on investments in prevention measures simultaneously involving several plants. The game between two neighbouring chemical plants and their strategic investment behaviour regarding the prevention of external domino effects is described and an illustrative example is provided. Recommendations are formulated to advance cross-plant prevention investments in a two-company cluster.

1. Introduction

In the chemical industry, economies of scope, environmental factors, social motives and legal requirements often lead companies to cluster. Therefore, chemical plants are most often physically located in groups and are rarely located separately. Moreover, due to the rapid development of chemical technology, there is a continuous growth of ever more complex installations with more extreme and critical process conditions, leading the incidence and the severity of major accidents to increase [1].

The most dangerous major accidents that can happen within chemical clusters are called domino effects, a term by which the potential for a knock-on interaction between groups of installations in the event of an accident at one of the installations is connoted. This mechanism is also referred to as 'escalation', 'interaction' or 'knock-on'. Domino risks or the risks associated with domino effects have a very high destruction potential. The study of domino effects is performed by investigating the different successive accidents, the so-called domino events, which constitute a domino effect [2–4]. While they have been recognised for a long time, the literature remains scarce and vague about the domino effect subject. There is no generally accepted definition of what constitutes domino effects, although various authors have provided suggestions. Table 1 presents an overview of current definitions identified in a review of relevant documents.

It is obvious that no unified understanding of the notion 'domino effect' exists within the research community. Different types of domino effects can in fact be distinguished in the definitions of Table 1: single-company (internal) domino effects and multi-company (external) domino effects. Whereas internal domino effects denote an escalation accident happening inside the boundaries of one chemical plant, external domino effects indicate one or more knock-on events happening outside the boundaries of the plant where the domino effect originates, as a direct or as an indirect result. Although the consequences of external domino effects can be devastating, this phenomenon has so far attracted very little attention of prevention managers in existing chemical clusters. The reason for this rather strange observation is threefold. First, the probability of external domino effects is extremely low and domino effects are thus perceived by prevention managers as 'extremely unlikely'. Second, modelling of external domino effects is highly complex and managers are often not inclined to carry out highly complex risk analysis techniques (especially not for phenomena perceived as extremely unlikely). Third, since several companies are possibly involved in such accidents, investigating them and obtaining the required data is often very difficult. As a result, companies are not inclined to invest more than legally required in preventing these extremely rare events.

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Table 1
Non-exhaustive list of domino effect definitions.

Author(s)	Domino effect definition
Third Report of the Advisory Committee on Major Hazards [5]	The effects of major accidents on other plants on the site or nearby sites.
Bagster and Pitblado [6]	A loss of containment of a plant item which results from a major incident on a nearby plant unit.
Lees [2]	An event at one unit that causes a further event at another unit.
Khan and Abbasi [7]	A chain of accidents or situations when a fire/explosion/missile/toxic load generated by an accident in one unit in an industry causes secondary and higher order accidents in other units.
Delvosalle [8]	A cascade of accidents (domino events) in which the consequences of a previous accident are increased by the following one(s), spatially as well as temporally, leading to a major accident.
AIChE-CCPS [9]	An accident which starts in one item and may affect nearby items by thermal, blast or fragment impact.
Vallee et al. [10]	An accidental phenomenon affecting one or more installations in an establishment which can cause an accidental phenomenon in an adjacent establishment, leading to a general increase in consequences.
Council Directive 2003/105/EC [11]	A loss of containment in a Seveso installation which is the result (directly and indirectly) from a loss of containment at a nearby Seveso installation. The two events should happen simultaneously or in very fast subsequent order, and the domino hazards should be larger than those of the initial event.
Post et al. [12]	A major accident in a so-called 'exposed company' as a result of a major accident in a so-called 'causing company'. A domino effect is a subsequent event happening as a consequence of a domino accident.
Cozzani et al. [13]	Accidental sequences having at least three common features: (i) a primary accidental scenario, which initiates the domino accidental sequence; (ii) the propagation of the primary event, due to "an escalation vector" generated by the physical effects of the primary scenario, that results in the damage of at least one secondary equipment item; and (iii) one ore more secondary events (i.e., fire, explosion and toxic dispersion), involving the damaged equipment items (the number of secondary events is usually the same of the damaged plant items).
Bozzolan and Messias de Oliveira Neto [14]	An accident in which a primary event occurring in primary equipment propagates to nearby equipment, triggering one or more secondary events with severe consequences for industrial plants.
Gorrens et al. [15]	A major accident in a so-called secondary installation which is caused by failure of a so-called external hazards source.
Antonioni et al. [16]	The propagation of a primary accidental event to nearby units, causing their damage and further "secondary" accidental events resulting in an overall scenario more severe than the primary event that triggered the escalation.

Nonetheless, external domino effects do happen. The worst such accident – in terms of death toll – occurred in Mexico City on November 19, 1984 [2]. It was an external domino effect involving three companies: the PEMEX plant (where the accident originated), the Unigas plant, and the Gasomatico plant. Another example is the Buncefield disaster, an accident involving external domino effects which happened near London (United Kingdom) in 2005 [4]. In the Buncefield case, a storage tank whereby the high-level alarm[1] did not function, was wrongfully heavily overfilled with gasoline during a long period of time. A substantial amount of gasoline flowed over, out of the tank, and evaporated, thereby forming a massive vapor cloud (in the vicinity of the storage tank). An operator noticing the vapor cloud initiated an alarm and as a result, the firewater pumps were automatically put in stand-by. These pumps were not constructed explosion-free and the pump house was located within the vapor cloud. Hence, starting the firewater pumps most probably caused the ignition of the vapor cloud. The subsequent explosion completely destroyed the firewater system and the overfilled storage tank. The consequent major fire then resulted in a domino effect of storage tanks fires and explosions. A large number of storage tanks of the depot (which was operated by several major chemical enterprises) was demolished. This accident is said to be the largest fire accident of peacetime Europe. The dense pall of smoke rose as high as 3000 m over the burning storage tanks where it originated from; the plume was so vast it appeared in satellite images of the scene. This accident has lead to estimated financial losses of approximately 2 billion euros. Readers who are interested in the Buncefield catastrophe are referred to the Buncefield investigation progress and recommendation reports [17–21].

Thus, accidents involving several plants do occur, and their human and economic loss potential is often many times greater than that of single plant escalation accidents. This observation certainly justifies the existence and the importance of scientific and professional studies helping to prevent devastating external domino effects, besides legal requirements on the one hand and all studies carried out and all measures in place in chemical plants to control and to manage internal domino effects on the other hand. With an increase in the density of chemical plants in a cluster and rising population densities worldwide, there is an urgent need for installing or increasing external domino effects prevention from a collaborative perspective. Although off-site (external) knock-on risks are investigated and evaluated by QRAs due to legal requirements, prevention managers indicate that the extreme low probabilities of their manifestation often leads to the conclusion that specific cross-plant preventive measures are unnecessary since preventive measures aimed at internal escalation are already in place. Specific situations may arise (e.g., due to the strategic value of the installation, due to requirements of control authorities, and due to other site-specific factors) where firms indeed will invest in the protection of their assets from external domino effects. However, there is still room for companies to collaborate on this topic and to substantially improve their investment approach. Ongoing research is thus necessary to control chemical risks involving several chemical plants. It is therefore crucial to investigate how to establish and to elaborate collaboration between neighbouring chemical companies as regards strategic prevention investments

[1] A high-level alarm serves to automatically stop feeding the tank in case a certain 'high level' of substance is present in the tank.

for external domino effects. No clear economic incentives exist to urge companies within chemical clusters to jointly develop multi-plant external domino risk management. To this end, this article is concerned with how to enhance external domino effects prevention measures involving two adjacent chemical plants, from a broad-based game-theoretical perspective.

It should be noted that the approach does not involve other parties than the two neighbouring companies. No other chemical plants, no surrounding communities, no public infrastructures (road, railways, and inland waterways) are thus involved in the approach. However, if the two companies implement highly effective domino effects preventive measures, other parties will benefit as well, be it in an indirect way.

This paper is structured as follows. Section 2 formulates the research question. Section 3 discusses the game which can be associated with external domino effects prevention in the case of two adjacent chemical plants and provides the required notions on game theory. Section 4 mathematically models the external domino effects investment game. Section 5 provides an illustrative example and Section 6 concludes this article.

2. Research question

Game theoretic modeling in combination with reliability theory has already been employed in scientific research to gain insights into the nature of optimal defensive investments that yield the best trade off between investment costs and security of critical infrastructures [22,23]. In a paper on reciprocal security-related prevention investment decisions, Reniers and Soudan [24] employ a meta-game theoretic approach to interpret and model behaviour of management of neighbouring plants while negotiating and deciding on reciprocal security investment decisions. However, to date, no attention has been paid to the cross-plant safety-related prevention decisions (concerning external domino effects) made by plant management of two neighbouring chemical companies using a game theoretic approach. Nonetheless, these decisions have an important impact on whether or not an external domino effect might take place and/or what consequences can be expected.

In real industrial settings, chemical clusters are often composed of more than two companies. Reniers et al. [25] discuss a game theoretic approach to interpret and model behaviour of chemical plants within chemical clusters composed of at least three chemical companies. Reniers et al. outline that if it is possible to change the strategic choice of a small number of players (companies) of the cluster as regards domino effects prevention, it might be possible this way to tip all the rest of the players within the cluster to change from a socially non-optimal situation to a socially optimal situation.

Risks as regards external domino effects between two chemical plants are risks whose consequences depend on a company's own risk management strategy and on that of the adjacent company. Expectations and perceptions about the neighbours' decisions will influence investments in cross-plant safety prevention measures. As a result, the socio-economic outcome might be sub-optimal for both companies. This situation of decision making of two neighbouring plants can be modeled as what is called a 'game' and – by solving the game – give conditions for a win-win situation or the so-called Nash equilibrium where both companies win by investing in external domino effects safety prevention measures. To develop an external domino effects investment approach in the case of two neighbouring companies, we need to analyze how a single chemical plant manages its external domino effect risks where there is likelihood that even if it has decided to invest in adequate measures, it might be harmed due to its neighbour not investing. It should be noted that a company, besides investing in prevention of domino effects initiated within its own fences, may decide to invest in reducing the consequences of domino effects initiated by a nearby company as well. This notion should be captured by our model as well.

Our research is aimed at predicting the external domino effect prevention outcome of a situation where both companies make independent decisions on whether to invest in such prevention or not, but are at the same time aware of the strategic external domino effect decisions (to 'invest' or to 'not invest') made by the other company. As already mentioned, in real industrial settings, chemical clusters are often composed of more than two companies. However, in the initial phase, domino effects prevention needs to be focused on two companies, since these two plants actually trigger the escalation effect, eventually involving more plants. Hence, if the triggering plants are able to contain the potential domino effect, no knock-on effect can affect the other plants within the cluster. In this paper, we therefore investigate strategic external domino prevention choices of two companies situated next to each other. In a later phase, larger clusters should be included in the exercise.

Due to the extremely low probabilities of an external domino effect occurring, company prevention advisors indicate that many[2] chemical plants are not inclined to invest in preventive measures besides those legally required. Assuming this is the case, companies believe that, whether their neighbour invests or does not invest in such measures, the companies' strategy to 'not invest' is always better than 'to invest'. Hence, in current industrial practice, in the external domino effect game played between two neighbouring chemical plants, the solution of the game seems to be for both companies to follow a strategy to 'not invest' in external domino effects prevention.

In this paper, our research question is therefore to investigate the possibility of giving recommendations on how to achieve a socio-economic optimal strategy of external domino effect prevention investment by adjacent chemical companies. To this end, an external domino effects investment approach has to be worked out.

3. Notions on game theory

Game theory is the theory of independent and interdependent decision making. Games of strategy are games involving two or more players, not including nature, each of whom has partial control over the outcomes. The external domino effect game can be classified as a two-person mixed-motive[3] game of strategy [26,27]. Even the simplest mixed-motive games, represented by two-by-two matrices, have many strategically distinct types. The are twelve distinct symmetrical two-by-two mixed-motive games, of which eight have single Nash equilibrium points[4] and four do not [29]. In our external domino effect case, we classify the game as a mixed-motive game without a single equilibrium point.

One archetype of such a game is a so-called 'martyrdom game'.[5] The most famous prototype of such game type is the prisoner's dilemma game. Such a game is characterized with a conflict between individual self-interest and collective self-interest. A martyrdom game has one Nash equilibrium point. Hence, the external

[2] As mentioned previously, situations may arise where firms indeed will invest in the protection of their assets from external domino effects for a variety of reasons.

[3] In a mixed-motive game, the sum of the pay-offs differs from strategy to strategy.

[4] The Nash equilibrium concept embodies two requirements [28]: (i) players' strategies must be a best response (i.e., should maximize the players' respective payoffs or should minimize their respective costs), given some well-defined beliefs about the strategies adopted by the other players, and (ii) the beliefs held by each player must be an accurate ex ante prediction of the strategies actually played by the other players.

[5] For specific situations where the external domino effects game is characterized by a costs matrix indicating it is not a martyrdom game, this specific game can of course be solved using the appropriate game-theoretical solving method.

domino effect prevention investment choices made by every individual chemical facility might lead to socio-economic optimal or sub-optimal situations. If the costs are sufficiently low (so that each company wants to invest in external domino effects prevention, even if the neighbouring company did not incur these costs) is a straightforward example of a socio-economic optimal situation. If external domino effects prevention investments would appear to be very high to both companies relative to their potential benefits, then it might be efficient for no company to incur investment costs (inducing a socio-economic sub-optimal situation). It should be noted that in this article a socio-economic optimal situation is a situation where society and economy is protected as good as possible at the optimal (minimized) cost against the devastating consequences of a major accident, in case an external domino effect.

In the external domino effects game the equilibrium representing both companies not investing is possibly socio-economically worse than another possible strategy where both players agree to invest, due to the conflict of individual self-interest and collective self-interest. The strategy where both companies optimize their collective pay-offs is however unstable, since each player is tempted to deviate from it (due to the very low probabilities of an external domino effect occurring, in combination with high investment costs to avoid such an accident). Although several boundary conditions (such as control by the authorities, and pressure of the public opinion) may strongly influence such an equilibrium, the temptation to deviate from it (looking at the costs matrix) rests present.

We classify the external domino effects game as a game of partial protection with negative externalities, whereby we define 'externalities' as possible effects that one company can have on another company (following [30]). The existence of possible external domino effects between two companies gives rise to negative externalities. An accident caused by a lack of domino effect prevention within one company can have catastrophic effects (i.e., 'negative externalities') on its neighbouring company. A Nash equilibrium exists for this kind of game theoretic problem. The interested reader is referred to Heal and Kunreuther [30].

4. External domino effects investment approach

Both of the neighbouring companies in our external domino effects game have a discrete strategy, S_i (i = 1 or 2), that can take as values either *I* or *NI*, representing investing in external domino effects prevention (*I*) and not investing in external domino effects prevention (*NI*), respectively. Consider two adjacent chemical companies. Let the factor $P_{i,j}$ represent the probability that an accident will occur in plant *j* caused by an accident which took place in plant *i* (in other words, $P_{i,j}$ is the likelihood of an external domino effect from company *i* to company *j*). If $i = j$, then the factor expresses the probability for an internal domino effect in company *i*. Every company can decide either to invest in external domino effect prevention or not. If company *j* does not invest, the pure investment cost of company *i* equals c_i^{jNI}. If company *j* does invest, the pure investment cost of company *i* equals c_i^{jI}, with $c_i^{jI} < c_i^{jNI}$ (due to possible benefits and efficiencies[6]). If an external domino accident takes place, the loss to company *i* equals L_i. For simplicity, external domino effect prevention measures are assumed to be completely effective. Hence, if external domino effect prevention investments are made in company *i*, no domino effect can originate from company *i* towards company *i* itself, as well as towards company *j*. This hypothesis is made such that the effectiveness of the domino effects preventive measures would have no influence on the perspective of the decision makers to make the investment decision.

To investigate whether it is possible in the two-company case study for obtaining a socio-economic optimal situation of both companies investing in external domino effect prevention, we have to establish under what conditions a Nash equilibrium point is obtained. Therefore, we draw the costs matrix of the game.

Assume we have two companies called 1 and 2. If both companies 1 and 2 decide to invest in external domino effects preventive measures, then their costs are just their investment costs, c_i^{jI} with $(i, j) = (1, 2)$ and $(2, 1)$. If company 1 invests in external domino effects prevention measures (initiated at the own company 1), and company 2 does not invest in external domino effects prevention measures (initiated at the own company 2), then company 1 incurs its investment cost c_1^{2NI} plus the expected loss of an accident which is initiated by an accident inside company 2 (i.e., $P_{2,1}L_1$). In such case, company 2 just has an expected loss from an accident initiated within the own company, i.e., $P_{2,2}L_2$. An analogous cost allocation can be made for company 1 not investing and company 2 investing. If neither company 1 and company 2 invest, then company 1 has an expected loss from (i) an accident initiated within the own company (i.e., $P_{1,1}L_1$), conditioned on there being no accident from company 2 onto company 1 (i.e., times $1 - P_{2,1}$), plus (ii) the expected loss from an accident from company 2 onto company 1 (i.e., $P_{2,1}L_1$), conditioned on there being no accident initiated within the own company (i.e., times $1 - P_{1,1}$).[7] The conditions result from the fact that a chemical installation can only explode or be destroyed once and that the internal and external accidents do not originate at the same time.

In case company *i* invests in prevention of external domino effects initiated at company *j*, then $P_{j,i}L_i$ will be zero. At the same time, company *j* investing or not, as a result of higher investment costs for company *i*, c_i^{jI} or c_i^{jNI} will be higher. Hence, using concrete figures, taking these extra preventive actions may change the results and the outcome of the theory. However, it should be noted that assumptions about investments for reducing the probabilities and/or consequences of external domino effects caused by the nearby company does not alter the theory's overall conclusions and its generic validity.

It should also be noted that due to the theoretical nature of this paper it is not important whether the investment costs are fixed investment costs or annual costs or whether they are direct or indirect costs or some combination of the above possibilities. For example we assume direct annual external domino effect prevention investment costs. The resulting costs matrix can be found in Fig. 1.

For this costs matrix, the strategy $\left\{NI, NI\right\}$ is a Nash equilibrium point under the conditions that:

$$\begin{cases} P_{1,1}L_1\left(1 - P_{2,1}\right) + P_{2,1}L_1\left(1 - P_{1,1}\right) < c_1^{2NI} + P_{2,1}L_1 \\ P_{2,2}L_2\left(1 - P_{1,2}\right) + P_{1,2}L_2\left(1 - P_{2,2}\right) < c_2^{1NI} + P_{1,2}L_2 \end{cases} \quad (1)$$

If these conditions are satisfied, companies 1 and 2 do not have an incentive to deviate from their strategy *NI* since, whatever strategy the other company has chosen, the Nash equilibrium is optimal (i.e., the costs are lowest). In Figure 1, the Nash equilibrium point is indicated in a grey rectangular.

[6] Both companies can agree on the lowest joint investments for adequate prevention and protection against external domino effects.

[7] Remark that the expected loss of company *2* for this situation can be calculated in a similar way.

Table 2
Possible scenarios and their attributes.

Scenario	Conditions	Martyrdom's game?	Stable equilibrium	Socio-economic optimal equilibrium
1	$c_1^{2I} < P_{1,1}L_1$ and $c_2^{1I} < P_{2,2}L_2$	No	(I, I) (NI, NI)	(I, I)
2	$P_{1,1}L_1 < c_1^{2I} < P_{1,1}L_1(1-P_{2,1}) + P_{2,1}L_1(1-P_{1,1})$ $P_{2,2}L_2 < c_2^{1I} < P_{2,2}L_2(1-P_{1,2}) + P_{1,2}L_2(1-P_{2,2})$	Yes	(NI, NI)	(I, I)
3	$P_{1,1}L_1(1-P_{2,1}) + P_{2,1}L_1(1-P_{1,1}) < c_1^{2I} < c_1^{2I} + P_{2,1}L_1$ $P_{2,2}L_2(1-P_{1,2}) + P_{1,2}L_2(1-P_{2,2}) < c_2^{1I} < c_2^{1I} + P_{1,2}L_2$	Yes	(NI, NI)	(NI, NI)
4	Other possible conditions	No	(NI, NI)	(I, I) (NI, NI)

Company 1 \ Company 2	I	NI
I	c_1^{2I} ; c_2^{1I}	$c_1^{2NI} + P_{2,1}L_1$; $P_{2,2}L_2$
NI	$P_{1,1}L_1$; $c_2^{1NI} + P_{1,2}L_2$	$P_{1,1}L_1(1-P_{2,1}) + P_{2,1}L_1(1-P_{1,1})$; $P_{2,2}L_2(1-P_{1,2}) + P_{1,2}L_2(1-P_{2,2})$

Fig. 1. Costs matrix of companies 1 and 2 for the external domino effects game.

The strategy NI is for both chemical enterprises a dominant strategy[8] under the conditions that:

$$\begin{cases} P_{1,1}L_1 < c_1^{2I} \\ P_{1,1}L_1(1-P_{2,1}) + P_{2,1}L_1(1-P_{1,1}) < c_1^{2NI} + P_{2,1}L_1 \\ P_{2,2}L_2 < c_2^{1I} \\ P_{2,2}L_2(1-P_{1,2}) + P_{1,2}L_2(1-P_{2,2}) < c_2^{1NI} + P_{1,2}L_2 \end{cases} \quad (2)$$

Furthermore, the external domino effects game is a martyrdom game under the conditions that:

$$\begin{cases} P_{1,1}L_1 < c_1^{2I} < c_1^{2NI} + P_{2,1}L_1 \\ P_{1,1}L_1 < P_{1,1}L_1(1-P_{2,1}) + P_{2,1}L_1(1-P_{1,1}) \\ P_{2,2}L_2 < c_2^{1I} < c_2^{1NI} + P_{1,2}L_2 \\ P_{2,2}L_2 < P_{2,2}L_2(1-P_{1,2}) + P_{1,2}L_1(1-P_{2,2}) \end{cases} \quad (3)$$

These conditions are satisfied if the probabilities of an external domino effect have such extremely low values that $c_i^{jI} > P_{i,i}L_i$. If the external domino effects game would be a martyrdom game, both companies have dominant strategies and one Nash equilibrium point. If one company deviates from the Nash equilibrium point, it suffers itself (i.e., it becomes a martyr) and benefits the adjacent company. If both neighbouring companies deviate from the Nash equilibrium point, the cost is lower for both ('martyrdom equilibrium point'). Remark that the adjacent companies may communicate with each other if they so choose in this type of game [32]. It makes no difference. The companies might agree to invest in external domino effects prevention before the game, but they will still choose selfishly to not invest when faced with the actual decision, if acting rationally.

We distinguish four theoretically possible scenarios that will be further discussed. Table 2 summarizes these possible scenarios.

[8] A dominant strategy is always an optimal strategy for a player, independent of another player's strategy [31].

Further details on the scenarios of Table 2 are given below. It should be stressed that each actual case of two adjacent chemical plants investigating their joint external domino effects investment policy, can be categorized into one of the four scenarios described. Once the companies (or the authorities) carried out the exercise of categorizing the situation of the two-plant cluster into one of the scenarios, depending on the identified scenario, the companies (or the authorities) may choose an external domino effects investment approach for this situation. At present, companies do not have the ability to (relatively easy) determine, from a theoretical point of view, the optimal strategic investment approach for dealing with cross-plant risks. The investment approach provided in this article offers this possibility.

4.1. Scenario 1

Scenario 1 represents a game with two stable equilibria, (I, I) and (NI, NI). This is a mixed-motive game of strategies and there is no dominant strategy in the game. If both players proceed to invest, the risk of external domino effects is reduced to zero. Under these conditions, the cluster is in an optimal socio-economic situation. In scenario 1, equilibrium (I, I) investments are lower for each player than equilibrium (NI, NI) costs. Since the approach is characterized with imperfect but complete information and is based on rationality,[9] both players will opt for a strategy to invest. The game is no longer a martyrdom game and the socio-economic optimum is reached. There is, therefore, no reason to use additional incentives to encourage companies to carry out joint investments in external domino effect prevention measures in this scenario.

4.2. Scenario 2

In scenario 2, the conditions are given for a martyrdom game and not investing is the dominant strategy for both players. If none of the companies invest (strategy = (NI, NI)), company 1 incurs a cost $P_{1,1}L_1\left(1-P_{2,1}\right) + P_{2,1}L_1\left(1-P_{1,1}\right)$ and company 2 incurs a cost $P_{2,2}L_2\left(1-P_{1,2}\right) + P_{1,2}L_2\left(1-P_{2,2}\right)$ per year. This is a stable Nash equilibrium. If one player deviates from this equilibrium, he becomes a martyr of the game. Nonetheless, the best socio-economic solution would be (I, I) since in that case companies only incur costs c_1^{2I} and c_2^{1I} per year, respectively, being lower than in the Nash Equilibrium. This socio-economic equilibrium is unstable as both companies intend to deviate from it, since in the situation where one company deviates and the other does not the incurred costs of the deviating company are further decreased (due to $P_{1,1}L_1 < c_1^{2I}$ and $P_{2,2}L_2 < c_2^{1I}$). In order to obtain the socio-economic situation, i.e., (I, I), incentives may be given. Possible incentives are establishing an institution at multi-plant-level dealing with cross-plant safety issues, awarding subsidies or demanding taxes, and stimulating or decouraging investments with insurance premium fluctuations.

[9] In game theory, rational behaviour refers to a consistency in decision-making. Consistent players are seeking to maximize their pay-offs [26].

As safety investments at multi-plant-level are characterized by game theoretical features, a good way to enhance multi-plant collaboration and external safety investments is to adopt a supra-plant approach. Reniers et al. [33] suggest to set up an institution at the cluster-level, the so-called Cluster Council or Multi-Plant Council, which would be responsible for a continuous follow-up of external safety improvements at the member companies. Due to its cross-plant trust inducing capability, the Multi-Plant Council might play a stimulating role to reach the socio-economic optimum. In-depth interviews with company experts indicate that chemical clusters worldwide lack such an institution. The Multi-plant Council or Cluster Council as it is suggested by Reniers et al. is not an existing body nor is it mandatory within any EU Member State. Its responsibilities and structures exceed those of any existing collaborative bodies. The interested reader is referred to [33].

The socio-economic optimal situation (I, I) may also be stabilized through granting subsidies or by lowering the insurance premiums. The size of subsidy can be easily inferred from the cost matrix:

$$\begin{cases} c_1^{2I} - S_1 < P_{1,1}L_1 \\ c_2^{1I} - S_2 < P_{2,2}L_2 \end{cases} \quad (4)$$

where S_1 is the subsidy or lowered premium difference for company 1 and S_2 is the subsidy or lowered premium difference for company 2. The amount must cover at least the additional costs of safety investments compared with the expected loss of an accident. In this case, the companies will move from a socio-economic sub-optimal situation towards an optimal equilibrium and decide to invest. The game has now mixed strategies and two stable equilibria. Assuming rationality, the stable equilibrium (I, I) will result.

Tax imposition or raising the insurance premium can lead to a stable equilibrium (I, I) as well. The precise amount is also easily deduced from the cost matrix:

$$\begin{cases} c_1^{2I} < P_{1,1}L_1 + T_1 \\ c_2^{1I} < P_{2,2}L_2 + T_2 \end{cases}$$

where T_1 is the tax or raised premium difference imposed on company 1 and T_2 is the tax or raised premium difference imposed on company 2. The company will have to pay a tax or an increased premium if it does not meet the standards of a socio-economic optimum. When the investment costs minus the additional costs imposed on a company are lower than the expected loss of an accident, this company will opt for investing.

Obviously, the government may choose to employ a combination of subsidies and taxes to achieve the desired investment behaviour. Similarly, insurance companies can also carry out a mixture of premium increase and reduction.

The in-depth interviews indicate that no joint investments are – or would be – made by companies unless they are – or would be – explicitly stimulated by the government or by insurance companies.

4.3. Scenario 3

In this situation the conditions are given for a martyrdom game. Both players will have the same dominant strategy, i.e., to not invest. This way, a stable Nash equilibrium results: (NI, NI). The Nash equilibrium is also the most optimal socio-economic situation in scenario 3 as the costs in this situation will be minimal anyway. Accordingly, using incentives in such a scenario is unnecessary.

4.4. Scenario 4

Costs to collaborate (and to obtain strategy (I, I)) will be higher than non-cooperation costs in scenario 4 for at least one of the two companies. In this case (NI, NI) becomes the stable Nash equilibrium offering the lowest-cost option and the companies have no reason to deviate from it.

Depending on the case, the government or de insurance company may scrutinize if it is socio-economically responsible to give incentives to either (or both) of the companies whereby the costs of collaboration are reduced to a level where jointly investing is, taking the incentives into account, more advantageous to the companies.

5. Illustrative example of the investment approach

5.1. Introduction

To illustrate the investment approach, as much information as possible on probabilities, losses and investments was obtained through in-depth interviews with safety managers of two neighbouring firms situated within the Antwerp seaport cluster. Both firms are top tier Seveso sites according to the Seveso II European Directive [34] with an excellent safety reputation and safety track record.

It should however be noted that, due to confidentiality concerns and the lack of information, it was impossible to acquire certain necessary data from the real industrial case. Hence, extrapolations and assumptions had to be made to be in possession of all necessary information to demonstrate the approach and its results.

As such, this section describes an illustrative example rather than an actual case-study. The example is provided for companies and/or authorities to understand the usefulness and the user-friendliness of the approach. Using detailed (confidential) information, a cluster of two plants can relatively easy carry out the calculations to draw joint external domino effect prevention investment conclusions.

5.2. LPG and external domino effects

The storage of liquefied petroleum gas (LPG) is associated with significant risks and the potential of internal and external domino effects. The illustrative example focuses on LPG-related domino effects. Company 1 holds twelve LPG storage spheres, whereas company 2 includes seven LPG storage spheres.

5.3. Determining the probabilities

5.3.1. Determining $P_{i,i}$

For this illustrative example, catastrophic ruptures are considered to be the relevant failure modes possibly leading to internal domino effects. Generic failure probabilities are available in both enterprises as regards these catastrophic ruptures. In order to determine the total probability of a catastrophic rupture in each plant, failure probabilities are summed for all the possible domino effect scenarios over all the LPG spheres per plant per year. The total probability of internal domino effects for company 1 amounted to 1.10×10^{-4} per year. For company 2 the probability of an internal domino effect was assessed to be 0.64×10^{-4} on a yearly basis.

5.3.2. Determining $P_{i,j}$

It is very difficult to quantify the escalation risk of an internal domino effect beyond the borders of the company. Quantitative historical data pertaining to these probabilities are lacking in scientific and in professional literature since external domino effects remain extremely rare. Although academic literature on impact probabilities of domino effects exist (e.g. [16,35–39]), information continues to be very theoretical by nature.

According to an estimation carried out in collaboration with the company specialists who joined to work on this example, $P_{1,2}$ = 5.50×10^{-6} per year, while $P_{2,1}$ is equal to 4.34×10^{-6} per year.

Company 1 \ Company 2	I	NI
I	c_1^{2I} ; c_2^{1I}	44,298 €/yr ; 903 €/yr
NI	7,562 €/yr ; 27,077 €/yr	7,860 €/yr ; 980 €/yr

Fig. 2. Cost matrix of the illustrative example.

More detailed calculations may indeed be performed but are not required considering the illustrative purposes of this example.

5.4. Determining the losses

Since experts from both companies did not have any notion on the financial impact of a major domino effect upon their company, historical loss figures are employed to quantify the monetary losses deriving from eventual domino effect consequences within each company. The potential financial losses for the first company in case of a domino effect were estimated at 68,777,800 €. The calculation is based on the costs made to repair and/or replace the affected chemical installations due to the disaster.

Similarly, the potential financial losses for company 2 were estimated at 14,068,186 €.

5.5. Determining the safety investment costs

Interviews revealed that both companies do not cooperate as regards investment costs in external domino effects prevention. As a result, both companies assumed the adjacent company not to invest in prevention measures for curbing external domino effects. In general, this is a conservative approach as a company is not always aware of any possible investments of its neighbours. If company 1 invests in such prevention measures and company 2 does not, company 1 has a cost c_1^{2NI}. This annual cost c_1^{2NI} for the safety of LPG sphere tanks at company 1 was estimated at 44,000 € by company 1 specialists. Analogously, the cost c_2^{1NI} for company 2 on account of the present LPG spheres was estimated at 27,000 € by company 2 experts.

5.6. Discussion of illustrative example

Using the above numerical data and filling them into the cost matrix of Fig. 1 results in Fig. 2.

A set of scenarios is further developed where c_1^{2I} and c_2^{1I} are regarded as variable parameters representing the costs in the situation where both companies collaborate and decide together on their investment strategies concerning external domino effects. The game is a martyrdom game under the conditions that:

$$\begin{cases} 7562 < c_1^{2I} < 44,298 \\ 903 < c_2^{1I} < 27,077 \end{cases}$$

The socio-economic optimum when both companies collaborate and when the investment costs are minimal, can only be obtained in scenarios 1 and 2.

Under the conditions $c_1^{2I} < 7562$ and $c_2^{1I} < 903$ (scenario 1), the game has two stable equilibria, namely (I, I) and (NI, NI). The equilibrium (I, I) investments are lower than the equilibrium (NI, NI) costs for both companies. Therefore, if acting rationally, the strategic game is no longer a martyrdom game and both enterprises will invest. Hence, there is no reason to introduce additional measures such as subsidies or taxes.

Scenario 2 denotes a martyrdom game and the question arises which incentives may encourage organizations to collaborate. One of the possibilities is the authorities granting subsidies or demanding taxes. Another possibility is insurance companies scaling back or up their insurance premiums. In the case-study, the size of the incentive for company i should be higher than $c_i^{jI} - P_{i,i}L_i$ € per year.

In scenario 3 both players have the same dominant strategy, i.e., to not invest. This results in a stable Nash equilibrium (NI, NI), which is also the most optimal situation to ensure cost efficiency.

In the case of a scenario previously not described, the collaboration costs in case of a strategy (I, I) are higher than the costs of non-collaboration for at least one of the two companies. In this case, the authorities may choose to encourage one or both companies with incentives to invest in external domino effects prevention.

In-depth interviews with the prevention managers of the participating companies show that there is currently no practical use of game theory to enhance safety within the two-plant cluster of the illustrative example.

6. Conclusions

This research examined the extent to which game theory is applicable to external safety policy within a two-company chemical cluster. From the moment there is some degree of interaction between the neighbouring companies, investment decisions can be described as a strategic game. In this article, we assume the external domino effects game to be a mixed-motive game without a single equilibrium point. In this case, stability in the strategic decisions of adjacent collaborating companies is experienced either when joint investments in the prevention of external domino effects can take place at a sufficiently low cost or when deliberate incentives are provided.

A cost matrix was developed using simple data. Based on this matrix, socio-economic optima and equilibria were determined. Enterprises do not automatically tend towards a socio-economic optimum, but they do aspire to obtain a stable equilibrium. Therefore, the article further explained the conditions to induce such a stable equilibrium also representing the socio-economic optimum (in situations where both companies do initially not collaborate). Inducing a change in a company's strategic investment behaviour can be achieved by introducing incentives. Companies can opt for a self-regulatory body, such as a supra-plant Multi-Plant Council. Thanks to the presence of such an organization, and its alleviating impact on confidentiality concerns, information regarding potential costs, accident probabilities and safety investments may be more easily exchanged, allowing neighbouring plants to draw cost matrices in a simple way, whereby socio-economic optima and Nash equilibria can be determined. Another conceivable incentive is for the government to stimulate enterprises to seek the socio-economic optimum. They can grant subsidies or demand taxes. The subsidy amount must cover at least the additional costs of investing in external domino safety compared with the expected losses of an accident. By setting premiums, insurance companies may have the same influence on strategic external domino effect prevention investment behaviour.

Building upon these findings, companies are able to develop an optimal cross-plant safety policy (eventually steered by incentives), which benefits themselves as well as the surrounding community at large. Industrial application of the external domino effects investment approach proposed in this paper might thus lead to lower investment costs and at the same time bring about a truly safer chemical cluster.

Future research will be carried out to further refine the proposed approach and to discuss more sophisticated real-life problems.

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