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A sequential-move game for enhancing safety and security cooperation within chemical clusters

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ABSTRACT

The present paper provides a game theoretic analysis of strategic cooperation on safety and security among chemical companies within a chemical industrial cluster. We suggest a two-stage sequential move game between adjacent chemical plants and the so-called Multi-Plant Council (MPC). The MPC is considered in the game as a leader player who makes the first move, and the individual chemical companies are the followers. The MPC's objective is to achieve full cooperation among players through establishing a subsidy system at minimum expense. The rest of the players rationally react to the subsidies proposed by the MPC and play Nash equilibrium. We show that such a case of conflict between safety and security, and social cooperation, belongs to the 'coordination with assurance' class of games, and we explore the role of cluster governance (fulfilled by the MPC) in achieving a full cooperative outcome in domino effects prevention negotiations. The paper proposes an algorithm that can be used by the MPC to develop the subsidy system. Furthermore, a stepwise plan to improve cross-company safety and security management in a chemical industrial cluster is suggested and an illustrative example is provided.

1. Introduction

From a safety point of view (implying 'incidental' accidents) as well as from a security perspective (implying 'intentional' accidents), cross-company accidents or accidents involving several chemical plants (minimum two) at once (so-called external domino effects) may cause devastating damage to these plants. Such accidents may give rise to huge financial losses as well as significant losses of human lives. It is thus essential to prevent the occurring of these unwanted events to the very best of a chemical plant's abilities. In fact, since several companies are involved in such unlikely happenings, it is to the best interest of all plants composing a chemical industrial cluster to join forces in optimizing cross-plant loss prevention and making it as effective and as efficient as feasibly possible. By collaborating, costs can be minimized due to collaboration benefits (joint investments, cut redundancies, joint training sessions, joint emergency exercises, etc.). Also, if companies decide to cooperate, safety and security can truly be optimized in a chemical cluster on an operational level (e.g. by exchanging information and data or implementing certain preventive measures), on a tactical level (e.g. by carrying out cross-plant risk assessments), as well as on a strategic level (e.g. make important long-term joint prevention and mitigation investments). 'Security' is explicitly mentioned in the paper since, although highly unlikely, the possibility of a terrorist attack on chemical installations or storage tanks within company A affecting company B, or indeed a simultaneous attack on both companies, causing a major external domino effect, can certainly not be excluded. If the terrorist has access to sufficient and accurate information, these scenarios may unfold.

However, Ref. [1] indicates that companies are not inclined to cooperate on all levels due to various reasons. Especially on a strategic level, firms are unwilling to cooperate due to trust and confidentiality concerns. Conceiving an easy-to-use and easy-to-understand approach for encouraging companies to collaborate as regards cross-plant accidents may thus be highly relevant. Companies situated in a chemical cluster may be provided collaboration incentives by a cluster safety and security governance structure.

In their paper on interpreting and modeling chemical plants' behavior within chemical clusters while negotiating and deciding on domino effects prevention investments, Ref. [2] prove that a so-called Tipping-Inducing Sub Cluster (TISC) theoretically may be formed. A TISC is a sub-cluster of a (larger) chemical cluster with the property that if all chemical plants belonging to that sub-cluster decide to invest in cross-plant prevention, then for all companies belonging to the entire chemical industrial cluster the best strategy

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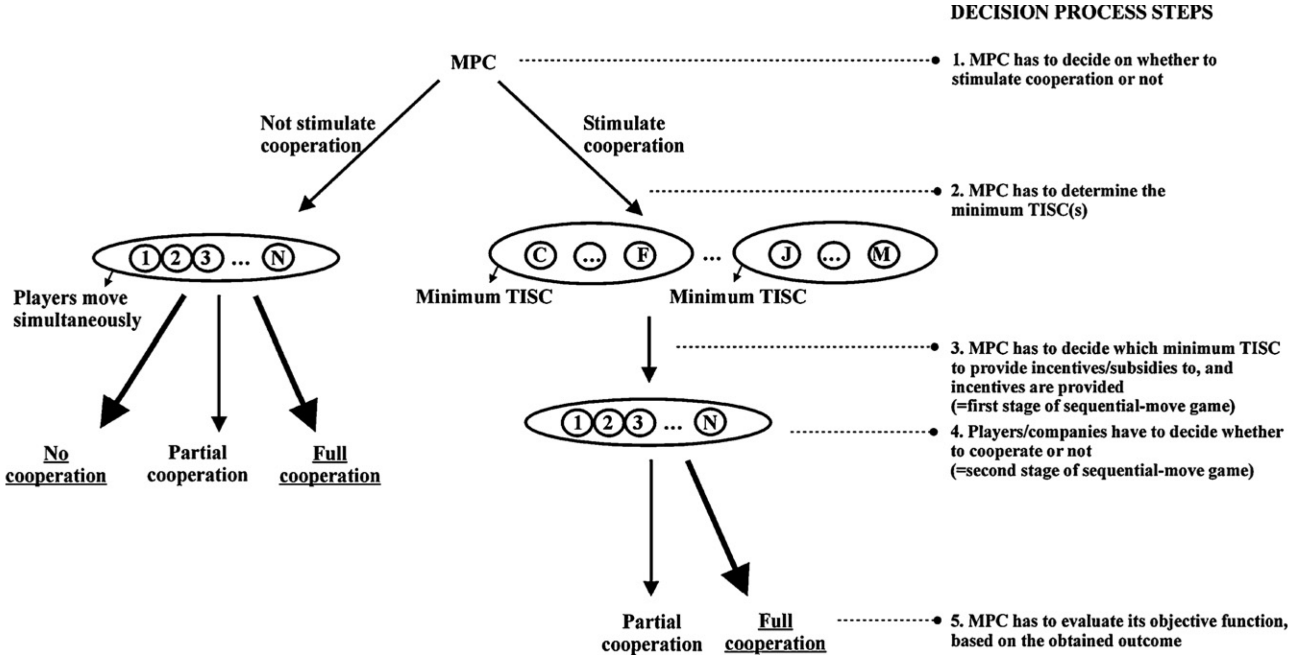

Fig. 1. Extensive form of the two-stage sequential move game.

is also to invest in such prevention. To prove the TISC's existence, Reniers et al. [2] employ a simplified situation of a 3-membered chemical cluster. Real-life chemical industrial clusters often consist of more than 3 companies situated in each others neighbourhood. Hence, the actual situation in real cluster cases is much more complex to deal with.

In this paper, we investigate whether it is possible to take more complicated situations into account by establishing the potential role of cluster safety and security governance. Cluster safety and security governance can actually be realized and implemented through self-regulation by a Multi-Plant Council (MPC). Reniers et al. [2–4] suggest setting up an institution at the multi-plant-level, the so-called Multi-Plant Council, which would be responsible for a continuous follow-up of external safety (and security) improvements at the individual companies belonging to the industrial multi-plant cluster. 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 as it is suggested by Reniers et al. [2–4] is not an existing body nor is it mandatory within any EU Member State or any US State. Its responsibilities and structures exceed those of any existing collaborative bodies. The MPC includes two parts. One part is composed of plant-representatives, while the other part consists of independent experts. These independent experts collect the necessary (confidential) information and can use it, for example, as input for executing computer-automated software, audits, inspections, etc., and also for playing the sequential-move game. Based on the output of the game, the independent part of the MPC can draw conclusions and make decisions. The interested reader is referred to Reniers et al. [2–4].

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 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 a so-called

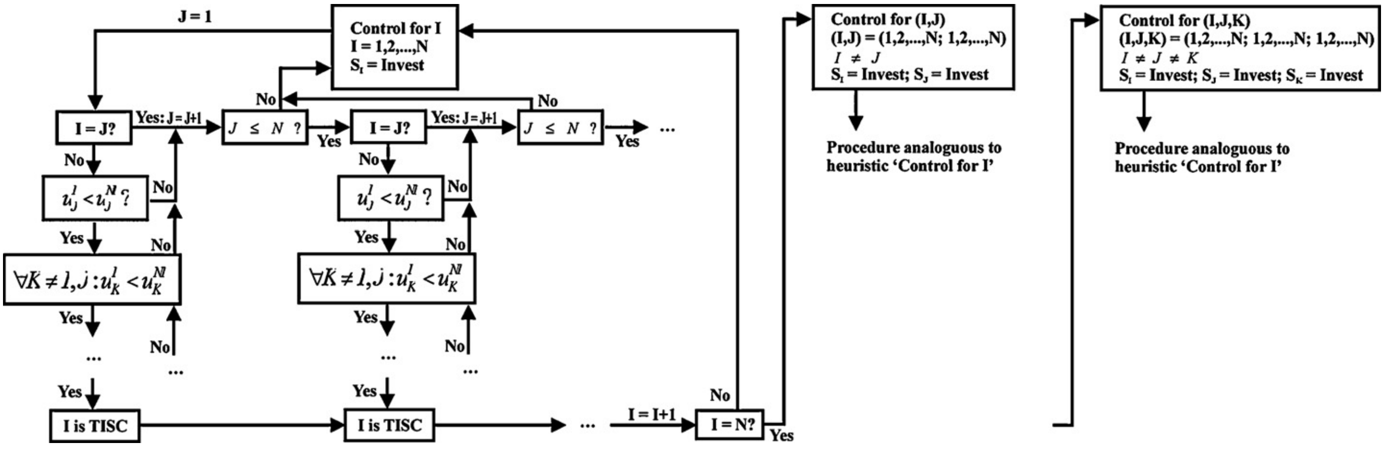

Fig. 2. Algorithm for determining all TISCs within a chemical industrial area.

Nash Equilibrium where both companies win by investing in cross-organizational prevention measures.

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 [5,6]. Reniers et al. [2] discuss a game-theoretic approach to interpret and model behavior of chemical plants within chemical clusters composed of at least three chemical companies. The authors 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.

Due to the extremely low probabilities of an external domino effect occurring, company prevention advisors indicate that many chemical plants are not inclined to invest in cross-plant preventive measures besides those legally required. Assuming this is the case, companies believe that, whether their neighbours invest or do not invest in such measures, the companies' strategy *Not invest* is always better than *Invest*. Hence, in current industrial practice, in the cross-plant accident game played between chemical cluster plants, the solution of the game seems to be for companies to follow a strategy *Not invest* in external domino effects prevention [1].

This paper is further organized as follows. In Section 2 a game theoretic interpretation of a conflict between safety and security in a chemical cluster and social cooperation is described. A two-stage sequential move game between the chemical plants and the MPC is introduced in Fig. 1. In the considered game the MPC is a leader player who has opportunity to decide to support or not cooperation among the cluster companies. The MPC's objective is to achieve full cooperation among players through establishing a system of incentives (e.g. subsidy system) at minimum expense. The individual chemical companies are followers. After the leader makes the move, the followers may decide to invest in cooperative prevention of domino accidents and play Nash equilibrium. The solution of the game is obtained as a subgame perfect equilibrium. To establish an optimal system of incentives, we search for a minimal coalition of players, whose initial decision to cooperate is sufficient to induce cooperation among the rest of the players, i.e., a so-called TISC [2]. Section 3 contains an algorithm of identifying the minimal TISC and the roadmap for cooperation enhancement. The algorithm is presented in Fig. 2 and then explained in detail. Section 4 contains an illustrative example, which describes a game between five heterogeneous companies (forming the considered multi-plant cluster) and the MPC. The purpose of the example is to demonstrate how such a stepwise plan given in Section 3 to improve cross-company safety and security management in a chemical industrial cluster can be implemented. Afterwards, the conclusive remarks are presented.

2. Two-stage sequential move game of domino effect prevention

We suggest a two-stage sequential move game between chemical plants and the Multi-Plant Council. The MPC is considered as a leader player who makes the first move, and the individual companies are followers. The MPC's objective is to achieve full cooperation among the players (i.e., chemical companies composing the industrial cluster) through establishing a subsidy system at minimum expense. The rest of the players rationally react to the subsidies proposed by the leader and simultaneously play Nash equilibrium.

Consider n chemical companies composing a chemical cluster $\{x\}$. Every company i ($i = 1,.,n$) is characterized by

(i) the probability P_{ii} that company i's lack of action can lead to an internally induced loss L_i, $L_i \geq 0$;
(ii) the probability P_{ji} that company j's lack of action can cause an externally induced loss L_i to the company $i, j \neq i$;
(iii) the investment c_i into cross-plant prevention, which not only secures company i from occurrence of a major accident with escalation potential, but also guarantees no cross-border effect from i to any other company in the cluster;
(iv) a 'bang-bang' strategy A_i that can take values Invest (I) or Not Invest (NI) into cross-plant prevention of company i.

A loss caused by an internal domino effect is called 'a direct loss', whereas a loss to other companies (caused by an external domino effect) is considered in this article as "an indirect impact" and is referred to as 'an indirect loss'. Let $l_i(\{y\}, A_i)$ be the expected indirect loss to a company i when it chooses a strategy A_i and y is a set of companies in the chemical cluster which choose strategy $I (y \subseteq x)$. Consider a stage game $\Gamma = \{A_1, ..., A_n ; u_1, ..., u_n\}$ from [2], where u_i (í = 1, ..., n) is a negative payoff (or cost) for player/company i. The cost for player i if it chooses strategy $A_i = I$, given players from a coalition y do so as well, and the rest of the players $x \backslash y$ choose NI, is:

$$u_i^y = c_i + l_i(\{y\}, I) \tag{1}$$

If player i its strategy is $A_i = NI$, its cost is:

$$u_i^{x \backslash y} = L_i P_{ii} \prod_{j \neq i, j \in x \backslash y} (1 - P_{ji}) + l_i(\{y\}, NI)(1 - P_{ii}) \tag{2}$$

In expression (2) the first term is an expected direct loss of the company i, and the second term is its expected indirect loss. To make a prediction about the strategy each player chooses, we determine the Nash equilibrium of the game and find out whether cooperation among companies belonging to a chemical cluster is a stable outcome of the game. According to [5] the 'domino effect' game can be classified as an investment game with positive externalities. 'Positive externality' means that the merging of a larger coalition from the smaller ones and/or single players creates a positive side effect on those actors who were not involved in the coalition process.

Companies' decisions to invest in domino effects prevention to decrease internal (intra-company) domino risks, also decrease external (cross-company) domino risks experienced by other companies within the cluster. Hence, the more companies that invest in domino prevention, the higher are the positive externalities in the system. It should be noted that if a player i has decided to invest in domino effect prevention and a player j has to decide whether or not to do likewise, then the higher the probability that j can benefit of preventive investment by i, the less likely it is that j will follow suit and invest as well. In contrast to [2] and [5] the domino effect game considered in this article is a game with multiple equilibria[1]. The cost structure of domino prevention implies that a player i's individual cost of preventive investment is lower than the damage to player i in the case that an internal domino accident would happen. In such a situation, it is obvious that if company i acts as a rational player, it is assumed to invest. All other players will follow suit. Additionally, if no player invests then player i does not have incentives to invest (alone). In such a case of conflict between safety and social cooperation among chemical companies within a chemical cluster, the game can be interpreted as a 'coordination game with assurance' [7], with full cooperation and non-cooperation as

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[1] We do not oppose the two types of games. Rather we adjust the features of the 'domino effect game' to explicitly include the possibility of multiple outcomes, more than just a stable pessimistic outcome.

two Nash equilibria. Thus investment in preventive measures can be considered as a public good and its provision is conditioned on whether other players also invest, or do not invest.

As already mentioned, the MPC aims at enhancing cooperation among the chemical plants of the chemical cluster by providing them with subsidies at minimum expense. The rest of the players/chemical companies who do not obtain any subsidies, are assumed to react rationally to the subsidies proposed by the MPC and simultaneously play Nash equilibrium. To provide game theory based guidance for the MPC, we are interested in a subgame perfect equilibrium in such a game.

Definition 1. Let $\Gamma = \{X_1, \ldots, X_n; f_1, \ldots, f_n\}$ be the n-player normal form game, where $X = X_1 \times \ldots \times X_n$ is the set of strategies profiles and f_i is the payoff function of player i. The strategy profile $(x_1^*, \ldots, x_n^*)$ is a *Nash equilibrium* if for each player i, x_i^* is player i its best response to the strategies specified for the $n-1$ other players, $(x_1^*, \ldots, x_{i-1}^*, x_{i+1}^*, \ldots, x_n^*)$:

$$f_i(x_1^*, \ldots, x_{i-1}^*, x_i^*, x_{i+1}^*, \ldots, x_n^*) \geq f_i(x_1^*, \ldots, x_{i-1}^*, x_i, x_{i+1}^*, \ldots, x_n^*)$$

for every feasible x_i that is, x_i^* solves

$$\max_{x_i} f_i(x_1^*, \ldots, x_{i-1}^*, x_i, x_{i+1}^*, \ldots, x_n^*).$$

In Definition 1, player i prefers strategy x_i^* to any other of his/her feasible strategies (or in other terms, strategy x_i^* maximizes player i its utility), given that the strategy choice of other players is fixed. In the game $\Gamma = \{A_1, \ldots, A_n; u_1, \ldots, u_n\}$ each player/company i's payoff is negative and given as cost function $-u_i$ ($i = 1, \ldots, n$). In such a case, the players will solve the dual expenditure minimization problem, thus, in the game $\Gamma = \{A_1, \ldots, A_n; u_1, \ldots, u_n\}$ the Nash equilibrium profile $(A_1^*, \ldots, A_n^*)$ is such that for every *i:*

$$u_i(A_1^*, \ldots, A_{i-1}^*, A_i^*, A_{i+1}^*, \ldots, A_n^*) \leq u_i(A_1^*, \ldots, A_{i-1}^*, A_i, A_{i+1}^*, \ldots, A_n^*)$$

where $\min\limits_{A_i} u_i(A_1^*, \ldots, A_{i-1}^*, A_i, A_{i+1}^*, \ldots, A_n^*)$.

Defintion 2. *Subgame perfect Nash equilibrium* is such equilibrium that players' strategies constitute a Nash equilibrium in every subgame of the original game.

Subgame prefect equilibrium may be found by backward induction, an iterative process for solving finite extensive form games or sequential games. First, the optimal strategy of the player who makes the last move of the game is determined. Second, the optimal action of the next-to-last moving player is determined taking the last player's action as given. The process continues in this way backwards in time until all players' actions have been determined.

Because simultaneous move games of coordination can have two possible equilibrium situations, a leader player can direct the outcome towards the one which is more preferable to its payoff. Heal and Kunreuther [5] and Reniers et al. [2] both give an insight into the potential role of a mediator in case of these types of games. The current paper transforms the original game and suggests an explicit way of describing objectives of the leader player, called the MPC in this article, as formulated in expression (3).

$$u_0 = -\sum_{i \in y} c_i + \sum_{i \in x} (u_i^x - u_i). \tag{3}$$

The objective function for the MPC is composed of two parts: the first term represents the MPC's costs of providing cooperation incentives to the sub-group $\{y\}$ of players, whereas the second term represents the MPC's benefits from players cooperating. The first term can be explained as follows. Due to the extremely low probabilities of an external domino effect occurring, players are not inclined to invest in cross-plant preventive measures. They have to be provided incentives equivalent in monetary terms to the expected costs of investment. Hence, the sum of the prevention investments costs c_i for all players in a TISC is the amount of subsidies required to tip these companies from strategy *Not Invest* to strategy *Invest*.

The second term describes the difference between expected costs of the players in the situation, which would be realized at the end of the game (u_i), and the losses in the undesirable situation when nobody cooperates (u_i^x). Given that the MPC's objective is to achieve full cooperation among players, its payoff can be justified since the MPC's benefits become larger if more players cooperate, and they are largest in the case that all players cooperate.

Now let us describe the extensive form of the game (see Fig. 1). In the terminal nodes the players and the MPC receive payoffs according to formulae (1)–(3).

As illustrated in Fig. 1, the MPC has two strategies: (i) to 'stimulate cooperation', and (ii) to 'not stimulate cooperation'. If the MPC chooses not to enhance collaboration within the cluster, the individual companies/players play a Nash equilibrium and the real situation may either lead to no cooperation (and no joint investment) or to full cooperation (joint investments). In current industrial practice (where no organization such as the MPC exists), the former situation exists in chemical industrial clusters. In the case the MPC chooses to invest and to stimulate collaboration within the cluster, a subset of players will be given incentives/subsidies on the condition that they cooperate. Such a subset of players should be a minimum Tipping-Inducing Sub-Cluster (minimum TISC) in terms of [2].

Definition 3. A *TISC* is a coalition with the property that if all of its members have a strategy *Invest*, then for all other individual players of the greater cluster where the TISC is part of, the best response is also to invest.

Definition 4. A *minimum TISC* is a TISC of which no subset is also a TISC.

According to this concept, the MPC can identify a group of players (/all groups of players), whose initial willingness to cooperate allows to sustain full cooperation. This observation suggests that an algorithm for determining a TISC in a sequential move game is one of the important steps to solving it.

In the next section, we present an algorithm that can be used by the MPC for determining TISCs. We consider a sub-game, which corresponds to the MPC's choice of strategy 'Stimulate collaboration'. In this sub-game, first a TISC composed of players from $\{y\}$ chooses to play 'Invest' and then the remaining $\{x/y\}$ group of players sequentially decides to cooperate or not to cooperate. If we assume that all TISCs have been successfully identified then the bold lines on the second stage in Fig. 1 describe Nash equilibria in each of two sub-games. Without loss of consistence we assume that in the second sub-game (when the MPC plays 'Not to stimulate cooperation') the players move simultaneously. It implies that none of the players has a right or commitment to decide before others and thus the coordination game has two possible outcomes: no cooperation and full cooperation. Later in Section 4, we discuss that without coordination in a form of a system of incentives, the players are not willing to switch from strategy 'Not invest' to 'Invest'.

3. TISC-algorithm and roadmap for cooperation enhancement within chemical industrial clusters

An algorithm was developed to determine all TISCs within a chemical industrial cluster. The algorithm is provided in Fig. 2.

The TISC-algorithm first verifies whether every company, as a single company, may act as a TISC. Suppose a player I is a TISC. To prove that I is a minimal TISC indeed, we need to show that if the player I plays 'Invest' then we can find another player J, other than I, who prefers playing ‘Invest’ to ‘Not Invest’. If such a player J exists then we need to check if there is a player K (other than I or J), which prefers to play ‘Invest’ to ‘Not Invest’ if the players I and J play ‘Invest’. The routine continues until all players from $\{x\}$ play ‘Invest’. If such a choice of player I, being ‘Invest’, can induce other players sequentially playing Invest as well, then player I is a TISC. Otherwise if there is no such a single player, we need to check all couples of players to be TISCs or not. In a similar way, we should assume that some players I and J from $\{x\}$ play ‘Invest’. Then we need to check if there is a player K other than I or J who will prefer ‘Invest’. Continuing in a similar way, all triples of companies are to be checked, etc. This process is repeated until all $(n-1)$-multiples are validated against having the potential of being a Tipping-Inducing Sub-Cluster. At the end of the algorithm, all possible TISCs within a chemical industrial cluster are identified. It is necessary to point out that a TISC always exists because the static game is a coordination game with assurance where both non-cooperative and cooperative outcomes are stable.

The next step is to determine the minimum TISCs, i.e., the TISCs of which no subsets are also TISCs. This stage can be carried out by simply comparing all TISCs one-by-one. If all minimum TISCs are determined, all information is available to the MPC to take incentive/subsidy decisions.

A stepwise plan or roadmap for stimulating safety and security cooperation can be set up. The roadmap consists of the following steps:

1. Fix the number of chemical companies where the MPC would like to enhance collaboration in-between.
2. Collect the required parameters from the companies to carry out the collaboration-enhancement study (i.e., potential losses, domino prevention costs, and domino accident probabilities).
3. Use the TISC-algorithm to determine all minimum TISCs.
4. Use the objective function of the MPC to identify those minimum TISCs that deliver the MPC optimal benefits.
5. Provide incentives/subsidies to the optimal TISC settled in the previous stage.
6. Once the game is played, evaluate the outcome and act accordingly.

These 6 steps can be used as a guide for an MPC to actively enhance collaboration between chemical companies in the field of external domino prevention investments. After evaluation of the outcome, the MPC may decide to provide incentives to a minimum TISC, which delivers the largest (positive) payoff to the MPC. Such a strategy is optimal for the MPC, since no other TISC containing the minimum TISC can increase the MPC’s payoff. Indeed, expression (3) tells us that including more companies other than those belonging to the minimum TISC can only increase costs of incentives but will have no benefit effects from companies’ cooperation. The complexity of the proposed TISC-algorithm increases combinatorial when the number of plants increases. The number of all possible combinations, which have to be tested in the TISC-algorithm, is 2^n-2 (with n the number of chemical companies). Given that in practice, n is a rather limited number, the proposed algorithm can be implemented.

4. Illustrative example

Let us assume that the cluster is composed of five companies $i=\{1,2,3,4,5\}$, characterized with the following estimates of the players:

$$P5\times 5=\begin{pmatrix} 1.1\times 10^{-4} & 0.055\times 10^{-4} & 0.055\times 10^{-4} & 0.055\times 10^{-4} & 0.055\times 10^{-4} \\ 0.055\times 10^{-4} & 1.1\times 10^{-4} & 0.055\times 10^{-4} & 0.055\times 10^{-4} & 0.055\times 10^{-4} \\ 0.043\times 10^{-4} & 0.043\times 10^{-4} & 0.64\times 10^{-4} & 0.032\times 10^{-4} & 0.04\times 10^{-4} \\ 0.043\times 10^{-4} & 0.043\times 10^{-4} & 0.032\times 10^{-4} & 0.64\times 10^{-4} & 0.04\times 10^{-4} \\ 0.025\times 10^{-4} & 0.025\times 10^{-4} & 0.02\times 10^{-4} & 0.02\times 10^{-4} & 0.8\times 10^{-4} \end{pmatrix};$$

$$\begin{array}{l} c=(1.3\times 10^4, 1.3\times 10^4, 10^4, 10^4, 0.78\times 10^4); \\ L=(1.6\times 10^8, 1.6\times 10^8, 10^8, 10^8, 10^8). \end{array}$$

Here, we assume that both costs of domino effect prevention as well as possible losses are given in euro.

Furthermore, we assume that players 1 and 2 on the one hand, and players 3 and 4 on the other hand, have similar probabilities, costs and losses. We now solve the two-stage sequential game backwards. First, 30 possible situations in the simultaneous-move game of ‘not stimulate cooperation’ are feasible. Here players’ costs are given as follows:

$$\begin{array}{l}
u_i^y(I_i, I_j, I_k, I_l, I_m)=c_i; \\
u_i^y(I_i, I_j, I_k, I_l, NI_m)=c_i+P_{mi}L_i; \\
u_i^y(I_i, I_j, I_k, NI_l, NI_m)=c_i+(P_{li}(1-P_{mi})+P_{mi}(1-P_{li}))L_i; \\
u_i^y(I_i, I_j, NI_k, NI_l, NI_m)=c_i+(P_{li}(1-P_{mi})(1-P_{ki}) \\
+P_{ki}(1-P_{li})(1-P_{mi})+P_{mi}(1-P_{li})(1-P_{ki}))L_i; \\
u_i^y(I_i, NI_j, NI_k, NI_l, NI_m)=c_i \\
+(P_{li}(1-P_{mi})(1-P_{ki})(1-P_{ji}) \\
+P_{ki}(1-P_{li})(1-P_{mi})(1-P_{ji}))L_i \\
+P_{li}(1-P_{mi})(1-P_{ki})(1-P_{ji})L_i; \\
u_i^x(NI_i, NI_j, NI_k, NI_l, NI_m)=(P_{li}(1-P_{mi})(1-P_{ki})(1-P_{ji})(1-P_{ii}) \\
+P_{ki}(1-P_{li})(1-P_{mi})(1-P_{ji})(1-P_{ii}))L_i \\
+(P_{mi}(1-P_{li})(1-P_{ki})(1-P_{ji})(1-P_{ii}) \\
+P_{ji}(1-P_{li})(1-P_{ki})(1-P_{mi})(1-P_{ii}) \\
+P_{ii}(1-P_{li})(1-P_{ki})(1-P_{mi})(1-P_{ji}))L_i; \\
u_i^{x\backslash y}(NI_i, NI_j, NI_k, NI_l, I_m)=(P_{li}(1-P_{ki})(1-P_{ji})(1-P_{ii}) \\
+P_{ii}(1-P_{li})(1-P_{ji})(1-P_{ki}))L_i+(P_{ji}(1-P_{ki})(1-P_{li})(1-P_{ii}) \\
+P_{ki}(1-P_{li})(1-P_{ji})(1-P_{ii}))L_i; \\
u_i^{x\backslash y}(NI_i, NI_j, NI_k, I_l, I_m)=(P_{ki}(1-P_{ji})(1-P_{ii}) \\
+P_{ji}(1-P_{ki})(1-P_{ii})+P_{ii}(1-P_{ji})(1-P_{ki})); \\
u_i^{x\backslash y}(NI_i, NI_j, I_k, I_l, I_m)=(P_{ji}(1-P_{li})+P_{ii}(1-P_{ji}))L_i; \\
u_i^{x\backslash y}(NI_i, I_j, I_k, I_l, I_m)=P_{ii}L_i.
\end{array}$$

This coordination with assurance game has two equilibria:

(i) *Pareto Efficient Nash equilibrium*: all players choose cooperation and they thus choose to invest in domino effects precautions:

$$\begin{array}{l}
u_1^y(I_1, I_2, I_3, I_4, I_5)=u_2^y(I_1, I_2, I_3, I_4, I_5)=13\,000; \\
u_3^y(I_1, I_2, I_3, I_4, I_5)=u_4^y(I_1, I_2, I_3, I_4, I_5)=10\,000; \\
u_5^y(I_1, I_2, I_3, I_4, I_5)=7800;
\end{array}$$

(ii) *Risk-dominant Pareto Inefficient Nash equilibrium*: each player chooses not to cooperate and thus chooses not to invest in domino effects preventive measures:

$$\begin{array}{l}
u_1^x(NI_1, NI_2, NI_3, NI_4, NI_5)=u_2^x(NI_1, NI_2, NI_3, NI_4, NI_5) \\
=20\,255.383; \\
u_3^x(NI_1, NI_2, NI_3, NI_4, NI_5)=u_4^x(NI_1, NI_2, NI_3, NI_4, NI_5) \\
=13\,869.336; \\
u_5^x(NI_1, NI_2, NI_3, NI_4, NI_5)=9899.669.
\end{array}$$

It is realistic to achieve full cooperation and indeed full cooperation is more preferable as it will bring a Pareto efficient outcome if all players act rationally (i.e., there is no other situation, which is more beneficial for all players). However, if one (or more) of the players fail(s) to collaborate, the other cooperating players will lose. Playing the ‘inefficient’ Nash equilibrium (*NI*,. . .,*NI*) is thus less risky for the players as the costs’ variance over the other players’ strategies is lower. Specifically, the Nash equilibrium, when all players choose to *Invest*, is Pareto optimal, while the other, when all players choose to *Not Invest*, is risk-dominant. Though the situation when all players cooperate is thus actually possible, observation of current industrial practice proves that the cooperative strategy is not credible [2,8–10] and the situation when all players play the Pareto-Efficient Nash equilibrium is highly unlikely.

The MPC knows that if it does not stimulate collaboration, all players play *Not Invest*, and thus the MPC’s payoff is zero (there are no incentive/subsidies costs and also no benefits ($u_i = u_i^x$) as no cooperation among players takes place).

Let us now consider an option when the MPC chooses to provide a group of companies with subsidies to switch from strategy ‘*Not Invest*’ to strategy ‘*Invest*’. The MPC identifies those players whose initial willingness to cooperate is required to make the rest of the players follow (i.e., the minimum TISCs). There may be one or several minimum TISCs due to the fact that the players of the game are heterogeneous. Looking at the payoff structure of the players in the simultaneous-move game without any cooperation stimulation, by using the TISC-determination algorithm we notice that if players (3,4) choose strategy *Invest*, then the rest of the players will follow suit.

Let us consider subset $S = \{3,4\}$: we notice that then for players 1 and 2 Invest becomes a dominant strategy:

$$u_1^{x\backslash y}(NI_1, NI_2, I_3, I_4, NI_5) = 18\,879.714 > u_1^{y}(I_1, NI_2, I_3, I_4, NI_5) = 14\,279.996;$$
$$u_2^{x\backslash y}(NI_1, NI_2, I_3, I_4, NI_5) = 18\,879.714 > u_2^{y}(NI_1, I_2, I_3, I_4, NI_5) = 14\,279.996.$$

Once players 1 and 2 join *S* then player 5 also prefers an option *Invest*

$$u_5^{x\backslash y}(I_1, I_2, I_3, I_4, NI_5) = 8000 > u_5^{y}(I_1, I_2, I_3, I_4, I_5) = 7800.$$

It is easy to check that there is no other subset of players, which could have the properties of a TISC. Additionally, subset *S* is also a minimum TISC. According to formula (3), the payoff of the MPC is $u_0 = 20\,000 - 30\,800 + 44\,024.388 = 33\,224.388$.

Following backward induction, the subgame-perfect equilibrium of the game is when the MPC plays ‘Stimulate cooperation’. In that case, subset $S = \{3,4\}$ will choose to cooperate (‘Invest in domino effects prevention’), and the rest of the players simultaneously or sequentially will choose to cooperate as well. Another candidate for sub-game perfect equilibrium (when the MPC plays ‘Not stimulate cooperation’ and the players play ‘cooperate’) can be eliminated because the MPC is informed that if it does not ‘Stimulate cooperation’, the only credible move of the players is to choose not to cooperate.

In this case, the MPC will decide to provide incentives only to the players from the minimum TISC $S = \{3,4\}$, since the MPC’s (positive) payoff cannot increase if incentives are provided for a wider subset of players. Such a decision is intuitively clear: from the matrix of probabilities *P* one may notice that chances that the companies 3 and 4 will experience the domino accident from other companies, are the smallest, while the costs of prevention are still rather high (compared with the other companies). Thus, companies 3 and 4 are least vulnerable in the system and may not be inclined to start cooperation without additional incentives, even though full cooperation is more preferable than non-cooperation.

5. Conclusions

The objective of the present paper is to provide a game theoretic analysis of strategic cooperation on safety and security within chemical industrial clusters. We suggest a two-stage sequential move game between adjacent chemical plants and the Multi-Plant Council, where the MPC is a leader player who makes the first move, and the individual chemical companies are the followers. The MPC’s objective is to achieve full cooperation among the players through establishing a subsidy system at minimum expense. The rest of the players rationally react to the subsidies proposed by the leader and simultaneously play a Nash equilibrium.

We show that such a case of a conflict between safety and security, and social cooperation, belongs to the ‘coordination with assurance’ class of games, and we explore the role of cluster governance in achieving a full cooperative outcome in domino effects prevention negotiations. The paper suggests an algorithm and a roadmap to improve cross-company safety and security cooperation as regards domino effects preventive measures in a chemical industrial cluster.

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