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A game-theory based Multi-plant Collaboration Model (MCM) for cross-plant prevention in a chemical cluster

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A B S T R A C T

The presented Multi-plant Collaboration Model uses game theory to evaluate different strategic cross-plant precaution collaboration situations. The model first assumes prevention management's perceptions as a premise to take cross-plant prevention decisions. Second, it employs information from the different plants and aggregates the data to determine possible financial collaboration benefits within the entire industrial area. By doing so, an application of the model by a suggested independent supra-plant council may enhance and realize cross-corporation precaution in chemical clusters.

1. Introduction

A domino risk can be described by the potential for an escalating interaction between groups of chemical installations in the event of an accident at one of the installations. For the interested reader, Reniers [1] provides an overview of domino effect definitions. To render the reader with a notion of what constitutes a domino effect in relation with the research described in this paper, the definition given by Delvosalle [2] can be used, which is formulated as "*a cascade of accidents 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*". A domino effect therefore implies a primary accident concerning a primary installation, inducing one or more secondary accident(s). The latter accident(s) concern either the primary installation (i.e. a temporary domino effect) or a secondary installation (i.e. a spatial domino effect). These secondary accidents can have their origin inside or outside the boundaries of the initiating plant. The former type of accident refers to an internal domino effect, the latter type of accident refers to an external domino effect. Since domino effects can have cross-company implications, it is obviously in the interest of adjacent chemical plants to invest in cross-corporation preventive measures. A domino risk is characterized by extremely small probabilities combined with extremely devastating consequences (be they financial, infrastructural and/or human).

In general, three types of accidents can be discerned:

(i) Type I: accidents where a lot of historical data is available;
(ii) Type II: accidents where little or extremely little historical data is available;
(iii) Type III: accidents where no historical data is available.

Consequences of type I accidents mainly relate to individual employees (e.g. most work related accidents), whereas the outcome of type II accidents may affect a plant within an organization or large parts thereof (e.g. large explosions, domino effects). For this sort of accidents the reader is referred to Lees [3], Wells [4], Kletz [5,6], Atherton and Gil [7], Reniers [8]. Type III accidents have an unprecedented and unseen impact upon the entire organization and upon society (e.g. the 1986 Chernobyl nuclear disaster, the 2010 BP Deepwater Horizon disaster, etc.).

Most internal and external domino effects belong to Type II accidents; nonetheless some external domino effects may even be categorized as Type III accidents (such as e.g. the 1985 Mexico

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City disaster and the 2005 Buncefield disaster[1]). Obviously, such accidents cannot be treated in the same way as Type I accidents. There is simply not enough information available to use regular risk management techniques for completely controlling these complex major risks. Moreover, even if all information could become available (which would be a theoretical assumption), risks can become controlled indeed, but not eliminated. Accidents displaying characteristics of very large consequences with very low probability values, still can become realized, and full protection is therefore needed in such case. Hence, due to the possibly very high consequences, such accidents should be avoided and prevented at all times and at any cost.

It is obvious that collaboration between adjacent plants to prevent (internal and external) domino effects in a chemical industrial cluster could save many lives and could avoid possibly huge accident costs. Conceptualizing how such preventive collaboration can be stimulated in real industrial practice (and implemented by participating companies) is the research problem at hand in this article. We therefore describe the process during which neighboring chemical companies have to decide whether or not to invest in measures that prevent domino-effects from happening. The purpose of this paper is then to establish a collaboration model based on game-theoretical insights. This model should enable chemical plants to cluster their investments in domino-accident prevention measures in order to decrease internal and external domino risks within an industrial area.

Next to avoiding domino accidents and their disastrous losses, an additional incentive for chemical plants to cooperate and to jointly invest in prevention measures are possible collaboration benefits. These benefits could for instance arise from a joint investment in cross-company prevention measures, a joint risk assessment, joint emergency and training sessions, cutting redundancies, etc. Due to the rapid development of complex chemical technology, there is a continuous growth of ever more complex installations. This increasing complexity as well as increasing competition leads to more extreme and critical process conditions which in turn result in an enhancement of the severity of domino effects [9]. Moreover, the growing density of chemical plants in a cluster increases prevention managers' awareness of the importance of investing in external domino effect prevention measures. However, according to Reniers [1], little attention has been paid to this type of accidents in current industrial practices due to several reasons: (i) prevention management (deciding about the company prevention budget) perceives the probability that an external domino effect might occur as too unlikely to invest in highly specific cross-plant prevention measures (which can actually be seen as denying the existence of Type II and Type III accidents); (ii) prevention managers are not inclined to jointly carry out domino effect risk analysis techniques and to jointly decide on precaution investments (due to practical and cultural difficulties and dissimilarities); (iii) external domino effects involve several installations in several chemical plants, and therefore financial information from different plants is needed to investigate prevention investment decisions. Chemical plant top- and middle management is however not inclined to distribute confidential financial information among other chemical plants.

As a result, current industrial practices show that chemical plants are not urged to invest in external domino effect prevention measures more than legally required. Nonetheless, being a Type II or Type III accident, a domino effect might not happen for the next 1,000,000 years, or it might happen tomorrow. If it would happen tomorrow, an unprepared organization might be driven out of business. It is thus essential to take the necessary precaution measures in the most cost-efficient and the most effective way. In this paper, analogously to Pavlova and Reniers [10], we suggest to use an independent supra-plant body to implement the model in a chemical cluster. The primary purpose of such supra-plant body or so-called Multi-Plant Council is to overcome confidentiality issues. To this end, the Multi-Plant Council is divided into two parts. A first part consists of plant representatives who mainly have a counselling function, formulating recommendations as a result of brainstorming sessions. The second part consists of independent and external consultants who are responsible for gathering, assessing and analyzing all relevant and confidential financial risk information from the chemical plants in the cluster. Such independent consultants can be e.g. experienced (operational and financial) risk analysts. By dividing the Multi-Plant Council into two parts, a balance between confidentiality and data information is targeted. Fig. 1 illustrates the different parts of the Multi-Plant Council. The interested reader is referred to Reniers [8,11].

An example of confidential information could be any type of financial information. This information, together with other types of information and data, can be used as input for the Multi-plant Collaboration Model (MCM) which is elaborated and explained in this paper. This model's primary objective is thus to achieve the best possible form of cooperation among the chemical plants in the cluster by means of the Multi-Plant Council.

We distinguish three types of cooperation regarding an investment in cross-company prevention measures. First, a cluster composed of chemical plants can fully cooperate, that is, all chemical plants in the cluster decide to invest in external domino effect prevention measures. Second, at least two, but not all, chemical plants belonging to the industrial area decide to cooperate and to invest in cross-plant precaution. Third, there is no cooperation at all regarding precaution investment in a chemical industrial park.

This paper is organized as follows. In Section 2, we discuss the use of game theoretical concepts in an industrial area composed of chemical plants. Section 3 describes the methodology of the Multi-plant Collaboration Model in more detail. This model is then demonstrated by illustrative examples in Section 4. Section 5 discusses the findings, and Section 6 concludes this article and provides recommendations and suggestions for future research.

2. Game theory used in chemical clusters

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. More precisely, a strategic game is one in which a single decision is made by each player, and each player has no knowledge of the decision made by the other players before making their own decision. Such games are referred to as simultaneous decision games because any actual order in which the decisions are made is irrelevant.

To describe the strategic game $\langle N, (S_i), (u_i) \rangle$, the following parameters need to be specified:

(i) the set of players, indexed by $i \in \{1, 2, \ldots, N\}$;
(ii) a pure strategy set, S_t, for each player;
(iii) payoffs u_i for each player i for every possible combination of pure strategies used by all players.

[1] It should be noted that accidents of a similar type or nature took place prior in time to the mentioned accidents of Buncefield and Mexico City. Nonetheless, we believe that the sheer scale of the consequences of accidents such as Buncefield, Mexico City, and for example also Chernobyl, Deepwater Horizon and the 9/11 terrorist attacks, surpassed the imagination of what was believed to be realistic at the time of their occurring, and therefore, that these accidents may be classified as type III. However, this interpretation may be subject to debate.

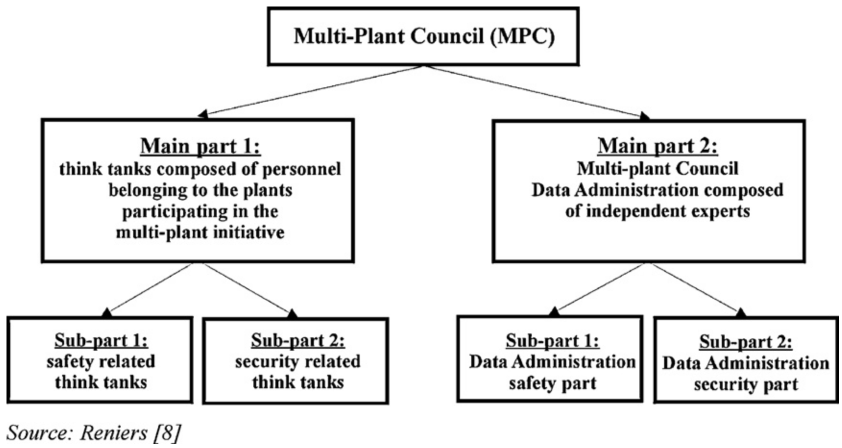

Fig. 1. Constitution of the Multi-Plant Council.

Source: Reniers [8].

We further specify the following definitions.

Definition 1. A **strategy** is a rule for choosing an action at every point that a decision might have to be made. A pure strategy is one in which there is no randomization.

Definition 2. A given preference relation on the set of action profiles of player i in a strategic game can be represented by a **payoff** function $u_i : \times_{i=1}^{N} S_i \to R$ (also called a utility function), in the sense that $u_i(a) \geq u_i(b)$ whenever a is preferred to b. We refer to values of such a function as payoffs (or utilities).

To keep the notation simple in this section (which purpose is merely to explain notions on game theory), we will concentrate on two-player games. Games with more than two players can be described similarly. In the two-player case, it is conventional to put the strategy of player 1 first and player 2 second so that the payoffs to player i are written $u_i(s_1, s_2)$, for any $s_1 \in S_1$ and $s_2 \in S_2$.

It is worth to note that we will focus mainly on finding the solution to the game in pure strategies.

A solution of a game is a (not necessarily unique) pair of strategies that a rational pair of players might use. Solutions can be denoted by enclosing a strategy pair within brackets, such as (s_1, s_2) in a two player game for instance. A solution is a systematic description of the outcomes that may emerge in a family of games. In strategic games the notion of solution captures a steady state of the play, in which each player holds the correct expectation about the other players' behavior and acts rationally.

It is reasonable to start solving games by eliminating poor strategies for each player by using the so-called *dominance principle*.

Definition 3. A strategy for player 1, s_1, **is dominated** by strategy s'_1 if for any $s_2 \in S_2$

$$u_1(s'_1, s_2) \geq u_1(s_1, s_2),$$

and there exists such $s'_2 \in S_2$ that

$$u_i(s'_1, s'_2) > u_i(s_1, s'_2).$$

That is, whatever player 2 does, player 1 is always better off using s'_1 rather than s_1. Similarly, we identify domination for player 2.

Some matrix games can be solved by the method of the elimination of dominated strategies.

To do so, we have to assume that:

(i) The players are rational;
(ii) The players all know that the other players are rational;
(iii) The players all know that the other players know that they are rational;
(iv) . . . (in principle) ad infinitum.

Furthermore, the concept of a Nash equilibrium can be defined.

Definition 4. A Nash equilibrium (for two player games) is a pair of strategies (s_1^*, s_2^*) such that

$$u_1(s_1^*, s_2^*) \geq u_1(s_1, s_2^*) \quad \forall s_1 \in S_1$$

and

$$u_2(s_1^*, s_2^*) \geq u_2(s_1^*, s_2) \quad \forall s_2 \in S_2.$$

In other words, given the strategy adopted by the other player, neither player could do strictly better (i.e. increase their payoff) by adopting another strategy. Nash equilibrium strategies are the best responses to each other.

The goal of this paper is to develop a model stimulating cooperation between two or more competing companies, leading to cross-plant precaution investments. Due to the interdependence of plants' strategy choices, collaboration benefits can be realized simply by gathering cross-plant information, processing it, and based on the calculations financially stimulating precaution cooperation within a chemical industrial area.

As already mentioned, in current industrial practice, on the one hand chemical plants in a cluster are not inclined to cooperate regarding external domino effect prevention measures, among others due to trust and confidentiality issues. Nonetheless, on the other hand external domino effects can only truly be minimized through collaboration between adjacent companies. The Multi-plant Collaboration Model that we envision therefore facilitates and stimulates cooperation among chemical plants by means of an independent supra-plant initiative and by using game theory. A collaboration model should take into account information from different companies at once and should consider different strategic collaboration options, in order to advise on optimized collaboration benefits.

In the MCM model, the players obviously are chemical plants and the utility functions are cost functions. Furthermore, companies have a discrete strategy, S_i, 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. In this article, we define a domino accident risk as the product of the probability of a domino event over a certain time interval (year) and the damage expressed in financial units (Euro). Hence, domino accident risks, and also domino prevention investment costs, are expressed in Euro per year.[2] Since the installations' lifetimes are thus factors to be taken into account when making a domino effect prevention decision, we assume that all chemical installations to be protected have still a minimum lifetime of at least one year (that is, at the time of making an *invest-or-not* decision). This is a reasonable assumption, since chemical installations, storage tanks, etc. in general are designed to have an average lifespan of at least several years, up to 10 years and more, depending on e.g. maintenance and other factors.

The cost functions used in the Multi-plant Collaboration Model are composed analogously to the model proposed by Reniers et al. [12]. Consider n chemical companies composing a chemical cluster $\{n\}$. Let the companies be indexed by i. Every company is characterized by:

(i) internal ($P_{i,}$) as well as external (P_j) domino accident probabilities that take into account the quantitative likelihood that a domino effect occurs. Internal domino accident probabilities take into account the likelihood of the occurrence of a domino effect that is initiated within plant i and only causes damage to installations and infrastructure in plant i. External domino accident probabilities, in turn, take into account the likelihood that a domino effect is initiated within plant i and causes damage within and outside the boundaries of the initiating company.
(ii) the potential losses (L_i) that are at stake in case a domino effect takes place. It is assumed that a domino effect is completely effective and destroys the entire company i. This is a very drastic assumption. In reality there will be a distribution of damages. For the sake of the argument the largest Expected Annual Loss, EAL, the product of likelihood and damage of each plant may for example be considered.
(iii) the investment in domino effects prevention at a cost C_i which leads for company i to avoidance of direct loss with certainty (it should be noted that C_i can thus be interpreted as a 'hypothetical benefit' of avoiding domino effects by investments in prevention). The model is conceptualized such that a company who has invested in domino effects prevention cannot cause an indirect impact on others.

If company i incurs a direct loss (by choosing not to invest), then this may also affect other companies' outcomes. If company i does not incur a direct loss then it will have no negative impact on other companies. The loss to other companies (caused by external domino effects) is considered as 'an indirect impact'. The latter implies that a company's investment cost is dependent on the strategy choices of the other chemical plants. Therefore, if every other company than company i invests in domino effects prevention, then company i cannot suffer indirect impacts (that is, impacts from other companies). Let the companies in the chemical sub-cluster $\{y\}$ be the only ones from the chemical cluster $\{n\}$ investing in domino effects prevention ($y \le n$).

Assume that all companies n in the chemical cluster invest in domino effects prevention (in such case is $y = n$). In that case, the investment costs of all companies n are C_i since both the internal and external domino accident probabilities reduce to zero. Otherwise, assume that not all chemical companies belonging to the cluster invest in domino effects prevention. Then, the expected cost of indirect impacts (consequences) to company i imposed by companies who do not invest in domino effects prevention is $\prod_{j \neq i, j \in \{n/y\}} (1-P_j) \cdot L_i$, whereby '$\prod$' refers to the summation of all indirect impacts caused by non-investing companies other than company i. Furthermore, the total expected investment cost of company i is dependent on its own strategy choice. On the one hand, if company i decides to invest in domino effects prevention when not all companies decide to invest as well, its total investment cost is $C_i + \prod_{j \neq i, j \in \{n/y\}} (1-P_j) \cdot L_i$. On the other hand, if company i decides not to invest in domino effects prevention in the situation of some companies not investing in domino effects precautions, its total investment cost is $P_i L_i \prod_{j \neq i, j \in \{n/y\}} (1-P_j) + \sum_{j \neq i, j \in \{n/y\}} (P_{ji} \cdot \prod_{k \neq i, k \in \{n/y\}} (1-P_{ki}) \cdot], (1-P_i) \cdot L_i)$. Hence, direct (internal) domino effects (the first term in the latter expression) are conditioned on the non-occurrence of indirect losses (i.e. $(1-P_j)$). Indirect effects (the second term in the latter expression) are conditioned on direct losses not occurring (i.e. $(1-P_i)$). These conditions result from the fact that a chemical installation can only explode or be destroyed once or that internal and external domino effects do not originate at the same time.

Furthermore, if a chemical company within a chemical cluster $\{n\}$ decides to invest in domino effects prevention, the expected indirect loss within the industrial park decreases. After all, every non-investing plant adds an additional domino risk to the cluster, and therefore an additional (implicit) cost on the total investment cost of the other plants situated in the cluster. This implies that collaboration benefits increase as the number of investing plants increases. A maximization of collaboration benefits, however, does not necessarily entail that the total investment costs of the individual plants is minimized.

Since the illustrative example in Section 4 employs a chemical cluster consisting of 5 companies (*Plant A*, *Plant B*, *Plant C*, *Plant D*, *Plant E*), Table 1 provides an overview of the various theoretical cost functions of *Plant A* in all possible strategic situations.[3]

3. Developing the Multi-plant Collaboration Model

The Multi-plant Collaboration Model to be developed should analyze whether collaboration is beneficial (in financial terms) and the outcome of the model, when showing a benefit, should stimulate cooperation or should have the potential to do so. In order to establish such a model that may stimulate cooperation among chemical plants, it is necessary to distinguish and define the various responsibilities of the stakeholders. First, the number of chemical plants in the cluster needs to be determined. Second, the plant representatives (e.g. prevention managers, financial analysts, top-management) should determine some important parameters (e.g. potential losses, direct investment costs, internal and external domino accident probabilities) to provide the MPC with the required information such that it is able to calculate the different cost functions.

This is a necessary step for the model, since only if all required confidential financial and operational information from all chemical plants in the cluster is delivered to the Multi-Plant Council Data Administration, it is possible for the independent experts of the MPC Data Administration to draw aggregated conclusions. The costs for *company i* as a consequence of non-investing plants (other than i) in the cluster cannot be calculated by a single plant i since the strategy choices of the other plants are uncertain and not known by that particular plant i.

The MPC is able to calculate collaboration benefits by determining the difference between the To-Be situation (i.e. cross-plant prevention investment costs following collaboration benefits obtained by applying the Multi-plant Collaboration Model) and the

[2] It should be noted that the required subsidies and/or taxes which can be determined to influence the collaborative prevention decision (see Section 4), are also expressed in Euro per year.

[3] A strategic situation is defined as a simultaneous strategy selection, one for each plant. Each strategic situation results in a different pay-off or investment cost for each player.

Table 1
Cost functions of *Plant A* in a 5 plant chemical cluster.

Strategic situation (*A*, *B*, *C*, *D*, *E*)	Cost functions of *Plant A*
(*I, I, I, I, I*)	C_A
(*I, I, I, I, NI*)	$C_A + P_{E,A}L_A$
(*I, I, I, NI, I*)	$C_A + P_{D,A}L_A$
(*I, I, NI, I, I*)	$C_A + P_{C,A}L_A$
(*I, NI, I, I, I*)	$C_A + P_{B,A}L_A$
(*I, I, I, NI, NI*)	$C_A + P_{D,A}L_A(1-P_{E,A}) + P_{E,A}L_A(1-P_{D,A})$
(*I, I, NI, I, NI*)	$C_A + P_{C,A}L_A(1-P_{E,A}) + P_{E,A}L_A(1-P_{C,A})$
(*I, NI, I, I, NI*)	$C_A + P_{B,A}L_A(1-P_{E,A}) + P_{E,A}L_A(1-P_{B,A})$
(*I, I, NI, NI, I*)	$C_A + P_{C,A}L_A(1-P_{D,A}) + P_{D,A}L_A(1-P_{C,A})$
(*I, NI, I, NI, I*)	$C_A + P_{B,A}L_A(1-P_{D,A}) + P_{D,A}L_A(1-P_{B,A})$
(*I, NI, NI, I, I*)	$C_A + P_{B,A}L_A(1-P_{C,A}) + P_{C,A}L_A(1-P_{B,A})$
(*I, I, NI, NI, NI*)	$C_A + P_{C,A}L_A(1-P_{D,A})(1-P_{E,A}) + P_{D,A}L_A(1-P_{E,A})(1-P_{C,A}) + P_{E,A}L_A(1-P_{C,A})(1-P_{D,A})$
(*I, NI, I, NI, NI*)	$C_A + P_{B,A}L_A(1-P_{D,A})(1-P_{E,A}) + P_{D,A}L_A(1-P_{E,A})(1-P_{B,A}) + P_{E,A}L_A(1-P_{B,A})(1-P_{D,A})$
(*I, NI, NI, I, NI*)	$C_A + P_{B,A}L_A(1-P_{C,A})(1-P_{E,A}) + P_{C,A}L_A(1-P_{E,A})(1-P_{B,A}) + P_{E,A}L_A(1-P_{B,A})(1-P_{C,A})$
(*I, NI, NI, NI, I*)	$C_A + P_{B,A}L_A(1-P_{C,A})(1-P_{D,A}) + P_{C,A}L_A(1-P_{D,A})(1-P_{B,A}) + P_{D,A}L_A(1-P_{B,A})(1-P_{C,A})$
(*I, NI, NI, NI, NI*)	$C_A + P_{B,A}L_A(1-P_{C,A})(1-P_{D,A})(1-P_{E,A}) + P_{C,A}L_A(1-P_{B,A})(1-P_{D,A})(1-P_{E,A}) + P_{D,A}L_A(1-P_{B,A})(1-P_{C,A})(1-P_{E,A}) + P_{E,A}L_A(1-P_{B,A})(1-P_{C,A})(1-P_{D,A})$
(*NI, NI, NI, NI, NI*)	$P_{A,A}L_A(1-P_{B,A})(1-P_{C,A})(1-P_{D,A})(1-P_{E,A}) + P_{B,A}L_A(1-P_{C,A})(1-P_{D,A})(1-P_{E,A})(1-P_{A,A}) + P_{C,A}L_A(1-P_{B,A})(1-P_{D,A})(1-P_{E,A})(1-P_{A,A}) + P_{D,A}L_A(1-P_{B,A})(1-P_{C,A})(1-P_{E,A})(1-P_{A,A}) + P_{E,A}L_A(1-P_{B,A})(1-P_{C,A})(1-P_{D,A})(1-P_{A,A})$
(*NI, NI, NI, NI, I*)	$P_{A,A}L_A(1-P_{B,A})(1-P_{C,A})(1-P_{D,A}) + P_{B,A}L_A(1-P_{C,A})(1-P_{D,A})(1-P_{A,A}) + P_{C,A}L_A(1-P_{B,A})(1-P_{D,A})(1-P_{A,A}) + P_{D,A}L_A(1-P_{B,A})(1-P_{C,A})(1-P_{A,A})$
(*NI, NI, NI, I, NI*)	$P_{A,A}L_A(1-P_{B,A})(1-P_{C,A})(1-P_{E,A}) + P_{B,A}L_A(1-P_{C,A})(1-P_{E,A})(1-P_{A,A}) + P_{C,A}L_A(1-P_{B,A})(1-P_{E,A})(1-P_{A,A}) + P_{E,A}L_A(1-P_{B,A})(1-P_{C,A})(1-P_{A,A})$
(*NI, NI, I, NI, NI*)	$P_{A,A}L_A(1-P_{B,A})(1-P_{D,A})(1-P_{E,A}) + P_{B,A}L_A(1-P_{D,A})(1-P_{E,A})(1-P_{A,A}) + P_{D,A}L_A(1-P_{B,A})(1-P_{E,A})(1-P_{A,A}) + P_{E,A}L_A(1-P_{B,A})(1-P_{D,A})(1-P_{A,A})$
(*NI, I, NI, NI, NI*)	$P_{A,A}L_A(1-P_{C,A})(1-P_{D,A})(1-P_{E,A}) + P_{C,A}L_A(1-P_{D,A})(1-P_{E,A})(1-P_{A,A}) + P_{D,A}L_A(1-P_{C,A})(1-P_{E,A})(1-P_{A,A}) + P_{E,A}L_A(1-P_{C,A})(1-P_{D,A})(1-P_{A,A})$
(*NI, NI, NI, I, I*)	$P_{A,A}L_A(1-P_{B,A})(1-P_{C,A}) + P_{B,A}L_A(1-P_{C,A})(1-P_{A,A}) + P_{C,A}L_A(1-P_{B,A})(1-P_{A,A})$
(*NI, NI, I, NI, I*)	$P_{A,A}L_A(1-P_{B,A})(1-P_{D,A}) + P_{B,A}L_A(1-P_{D,A})(1-P_{A,A}) + P_{D,A}L_A(1-P_{B,A})(1-P_{A,A})$
(*NI, I, NI, NI, I*)	$P_{A,A}L_A(1-P_{C,A})(1-P_{D,A}) + P_{C,A}L_A(1-P_{D,A})(1-P_{A,A}) + P_{D,A}L_A(1-P_{C,A})(1-P_{A,A})$
(*NI, NI, I, I, NI*)	$P_{A,A}L_A(1-P_{B,A})(1-P_{E,A}) + P_{B,A}L_A(1-P_{E,A})(1-P_{A,A}) + P_{E,A}L_A(1-P_{B,A})(1-P_{A,A})$
(*NI, I, NI, I, NI*)	$P_{A,A}L_A(1-P_{C,A})(1-P_{E,A}) + P_{C,A}L_A(1-P_{E,A})(1-P_{A,A}) + P_{E,A}L_A(1-P_{C,A})(1-P_{A,A})$
(*NI, I, I, NI, NI*)	$P_{A,A}L_A(1-P_{D,A})(1-P_{E,A}) + P_{D,A}L_A(1-P_{E,A})(1-P_{A,A}) + P_{E,A}L_A(1-P_{D,A})(1-P_{A,A})$
(*NI, NI, I, I, I*)	$P_{A,A}L_A(1-P_{B,A}) + P_{B,A}L_A(1-P_{A,A})$
(*NI, I, NI, I, I*)	$P_{A,A}L_A(1-P_{C,A}) + P_{C,A}L_A(1-P_{A,A})$
(*NI, I, I, NI, I*)	$P_{A,A}L_A(1-P_{D,A}) + P_{D,A}L_A(1-P_{A,A})$
(*NI, I, I, I, NI*)	$P_{A,A}L_A(1-P_{E,A}) + P_{E,A}L_A(1-P_{A,A})$
(*NI, I, I, I, I*)	$P_{A,A}L_A$

As-Is-situation (i.e. cross-plant precaution investment costs as they are today and without collaboration benefits).

The investment costs for the chemical plants in the As-Is situation depends on the criteria and perceptions on which company prevention management bases its current prevention strategy choice. One consequently needs to determine what are the criteria and perceptions on which prevention managers currently base their cross-plant prevention investment decisions on. We refer to these criteria and perceptions as the 'decision factors' for company prevention management.

The human mind deals with uncertainty, risks and decisions by resorting to a set of heuristics [13]. A heuristic is a sort of mental shortcut that in man's simpler, hunter-gatherer times probably sufficed for a variety of situations, and still does today. A related concept is *bias*, that is, a tendency to think and behave in a way that interferes with rationality and impartiality. In this paper, we try to take into account the biases of prevention management and use them to obtain an idea of the mind-heuristic that is being used by decision-makers to decide on cross-plant precautions.

Furthermore, we assume decision-makers to be risk-neutral and thus, their risk attitude will have a certainty equivalent equal to the expected value of an outcome. From this, we assume that the utility of a certain strategy (*I* or *NI*) is linearly proportional to its cost. Eq. (1) indicates how theoretically identical chemical plants in an industrial area can determine their annual investment cost in prevention measures in any strategic situation.

$$\begin{cases} u_i(I) = C_i + (n-(q+1)) \cdot P_j L_i \cdot ((1-P_j)^{(n-q-2)}) \\ u_i(NI) = P_i L_i (1-P_j)^{(n-(q+1))} + (n-(q+1)) \cdot P_j L_i \cdot (1-P_i)((1-P_j)^{(n-q-2)}) \end{cases} \quad (1)$$

We derive two equations since a plant can still choose two strategies regardless of the strategy choices of the other plants. The first equation is used in case a plant decides to invest. The second equation is used in case a plant decides not to invest. Although these equations only hold for a homogeneous chemical cluster (i.e. a cluster composed of *n* identical chemical plants), the decision factors are applicable to both a homogeneous and a heterogeneous (i.e. a cluster composed of *n* chemical plants which are not all identical) chemical cluster, since they actually relate to perceptions by individuals (and it does not make a difference in this context whether the adjacent plant is identical or not).

In the equations, $u_i(I)$ and $u_i(NI)$ connote the negative pay-off or annual investment cost for plant *i* dependent on its strategy choice (either *Invest* or *Not Invest*) as well as the strategy choices of the other plants. Furthermore, we propose the use of the *n*-value and the *q*-value. The former indicates the total number of plants participating in the chemical cluster, the latter indicates the total number of plants deciding to invest next to *Plant i* ($0 \leq q \leq (n-1)$).

Next, we determine the decision factors for prevention management by using these equations. First, we assume that prevention management perceives the probability of an external domino effect to be much lower than the probability of an internal domino effect. Since the latter (internal domino effect) already is perceived as extremely low, there are – at best – obviously insufficient prevention investments for such accidents. Thus, prevention management approximates P_j by zero in its perception. Therefore,

$$\begin{cases} u_i(I) \approx C_i \\ u_i(NI) \approx P_i L_i \end{cases} \quad (2)$$

The latter equations show in a simplified way the decision factors for prevention management. The reader should be aware that neither internal or external domino accident probabilities nor the common terms in Eq. (1) are negligible in real industrial practice, but that these approximations follow from individuals' perceptions. Eq. (2) shows that the decision to invest or not in cross-company prevention from a prevention managers' point of view is solely dependent on whether or not it is cheaper to either invest in domino prevention measures (and pay an investment cost C_i) or not (and risk a cost resulting from an internal domino effect, that is, P_iL_i). A chemical plant will therefore invest in prevention measures if $C_i \leq P_iL_i$ and will decide not to invest in case $C_i > P_{i,}L_i$. Finally, it is essential to note that expressions (2) show that the deduced decision factors are also applicable to a heterogeneous cluster. These decision factors serve as important background knowledge for the Multi-plant Collaboration Model.

The investment costs for the various chemical plants in the As-Is situation are compared by MCM with the investment costs in the To-Be situation. The To-Be investment costs are simulated by the supra-plant body. The investment costs in the To-Be situation are those in which the total investment costs of the cluster are minimized. This way, the collaboration benefits are maximized compared to the As-Is situation (where there may be collaboration benefits present, but no optimization is guaranteed). It should be noted that most probably in real industrial practice collaboration benefits are not at all maximized. A chemical plant obviously 'wins' in case its precaution investment cost in the To-Be situation are lower than its precaution investment cost in the As-Is situation. A chemical plant facing a lower investment cost in the As-Is situation compared to the To-Be situation, obviously faces a deficit. In a chemical cluster, a plant should never lose as a consequence of cooperation. The MPC Data Administration therefore needs to use the surpluses to compensate the deficits so that no plant individually loses compared to the As-Is situation. The remaining collaboration benefits can then be linearly divided over the various plants belonging to the cluster. The individual investment costs are then again compared to the As-Is situation and the cooperation type (full-, partial- or no cooperation) of the cluster is determined. The MCM does not rely on external incentives such as subsidies or taxes or insurance fee incentives (possibly provided by authorities or by insurance companies, respectively) to stimulate cooperation.[4] The suggested Multi-plant Collaboration Model is thus an autonomous model stimulating cooperation among chemical plants in a cluster solely by means of distributing the collaboration benefits. For this reason, it is not possible in every situation to stimulate cooperation by means of the proposed model. Some situations do require financial interference external to the cluster. To illustrate the model's applicability, the next section gives examples of different cluster situations.

The starting point of the analysis by the MPC is to investigate the strategic situation occurring when no supra-plant body would be present in the chemical cluster. As indicated before, we assume in this research that company prevention management bases its decision whether or not to invest in external domino prevention measures basically on the difference between the direct investment cost and the internal domino effect costs they face in case they do not invest.

We therefore distinguish four situations in the Multi-plant Collaboration Model:

(i) It is for every plant in the cluster less costly to invest in prevention measures than to risk an internal domino effect;
(ii) It is for some plants (but not for all of them) less costly to invest in prevention measures than to risk an internal domino effect. However, the collaboration benefits of the chemical cluster are maximized in a strategic situation where all plants invest in domino effect prevention (we call this "*full cooperation*");
(iii) It is for some plants (but not for all of them) less costly to invest in domino prevention measures than to risk the costs and probabilities of an internal domino effect. However, a situation where all plants fully cooperate with regard to domino effect prevention does not maximize the collaboration benefits of the chemical cluster (this can lead to a situation of full cooperation or of partial cooperation);
(iv) It is for every plant in the cluster more expensive to invest in prevention measures than to risk the costs and probabilities of an internal domino effect.

The implications and the resulting type of cooperation of these situations are illustrated in the next section.

4. Illustrative examples

In this section, the simplicity, user-friendliness and usefulness as well as the limitations of the MCM are illustrated by means of four examples. In these examples, we assume a chemical cluster composed of five heterogeneous chemical plants (Plant A, Plant B, Plant C, Plant D and Plant E) with each specific required parameters. In a cluster composed of 5 plants we distinguish 32 (i.e. 2^5) strategic situations for every plant and therefore a total of 164 cost functions (i.e. 5×2^5). To improve comparability over the three situations in Fig. 2 we use identical internal and external probabilities as well as identical potential losses for each of the four 'Illustrative examples/Situations', described and discussed hereafter.

In Table 2, the plants designated in the rows initiate the domino effects, while the plants designated in the columns suffer losses from the initiating plant. For example, the probability that a domino accident in Plant C causes damage to Plant E is: $P_{C,E} = 1.20 \times 10^{-6}$ per year.

4.1. Illustrative example/Situation (i)

Situation (i) describes an example in which the *single company invest* – strategy results in the lowest possible investment cost for all plants. We assume thus that every plant directly invests in domino prevention measures and does not risk a domino effect because it is in the perception of company prevention management less expensive to invest than to not invest. Assume the following investment costs for five chemical plants belonging to the same industrial area:

Direct investment cost:
Plant A: $C_A = 16{,}000$ €/year
Plant B: $C_B = 22{,}000$ €/year
Plant C: $C_C = 48{,}000$ €/year
Plant D: $C_D = 68{,}000$ €/year
Plant E: $C_E = 103{,}000$ €/year

In this situation, the corresponding As-Is situation for these parameters is equal to the strategic situation (*I*, *I*, *I*, *I*, *I*). When the MPC Data Administration carries out the MCM simulation and calculates the various cost functions derived by using game-theoretical modeling, the corresponding investment costs for every plant in every strategic situation are calculated. This result is shown in Fig. 2.

Fig. 2 indicates that the To-Be situation in this example is actually the situation in which all plants do invest in external domino effects precaution, that is, the As-Is situation. Since the As-Is situation and the To-Be situation are identical in this situation, there is no real use for the MCM. In this example, the prevention managers would individually choose to invest and by doing so already inadvertently maximize the collaboration benefits.

[4] The MPC obviously needs to have an internal working budget for its base cost of existence (man hours, office, etc.), but we assume that there is no external 'incentive budget' available that can be used by the MPC to stimulate domino prevention collaboration between companies.

Strategic situations	*Plant A*	*Plant B*	*Plant C*	*Plant D*	*Plant E*	Total Investment
(I, I, I, I, I)	**16000.00**	**22000.00**	**48000.00**	**68000.00**	**103000.00**	**257000.00**
(I, I, I, I, NI)	16144.00	22968.00	48162.00	68484.00	142500.00	298258.00
(I, I, I, NI, I)	16768.00	22836.00	48432.00	79200.00	104691.00	271927.00
(I, I, NI, I, I)	16544.00	22473.00	51300.00	69672.00	103475.00	263464.00
(I, NI, I, I, I)	16400.00	23100.00	48729.00	68836.00	103304.00	260369.00
(I, I, I, NI, NI)	16912.00	23803.99	48594.00	79683.65	144188.46	313182.10
(I, I, NI, I, NI)	16688.00	23440.99	51461.88	70155.99	142974.29	304721.15
(I, NI, I, I, NI)	16544.00	24067.59	48891.00	69320.00	142803.54	301626.13
(I, I, NI, NI, I)	17311.99	23308.99	51731.67	80870.80	105165.99	278389.45
(I, NI, I, NI, I)	17168.00	23935.65	49161.00	80035.40	104994.99	275295.03
(I, NI, NI, I, I)	16944.00	23572.80	52028.45	70507.99	103779.00	266832.23
(I, I, NI, NI, NI)	17455.99	24276.97	51893.55	81354.44	144662.74	319643.69
(I, NI, I, NI, NI)	17311.99	24903.23	49322.99	80519.05	144492.00	316549.26
(I, NI, NI, I, NI)	17088.00	24540.39	52190.32	70991.98	143277.83	308088.51
(I, NI, NI, NI, I)	17711.99	24408.44	52460.11	81706.18	105469.98	281756.71
(I, NI, NI, NI, NI)	17855.99	25376.01	52621.99	82189.82	144966.28	323010.09
(NI, NI, NI, NI, NI)	**19455.58**	**25628.90**	**53498.80**	**83640.74**	**146502.93**	**328726.94**
(NI, NI, NI, NI, I)	19311.61	24661.33	53336.93	83157.10	107008.94	287475.92
(NI, NI, NI, I, NI)	18687.76	24793.27	53067.14	72443.94	144814.51	313806.62
(NI, NI, I, NI, NI)	18911.71	25156.11	50200.48	81969.98	146028.66	322266.94
(NI, I, NI, NI, NI)	19055.67	24529.96	52770.37	82805.37	146199.40	325360.77
(NI, NI, NI, I, I)	18543.79	23825.69	52905.27	71959.95	105317.99	272552.69
(NI, NI, I, NI, I)	18767.74	24188.54	50038.48	81486.34	106533.96	281015.06
(NI, I, NI, NI, I)	18911.71	23561.99	52608.50	82321.73	106704.96	284108.88
(NI, NI, I, I, NI)	18143.88	24320.48	49768.49	70771.98	144340.23	307345.06
(NI, I, NI, I, NI)	18287.85	23693.99	52338.71	71607.96	144510.97	310439.48
(NI, I, I, NI, NI)	18511.80	24056.98	49471.49	81134.60	145725.13	318899.99
(NI, NI, I, I, I)	17999.91	23352.89	49606.49	70287.99	104843.00	266090.28
(NI, I, NI, I, I)	18143.88	22726.00	52176.83	71123.98	105013.99	269184.68
(NI, I, I, NI, I)	18367.83	23089.00	49309.49	80650.95	106229.97	277647.25
(NI, I, I, I, NI)	17743.97	23221.00	49039.50	69935.99	144036.69	303977.15
(NI, I, I, I, I)	17600.00	22253.00	48877.50	69452.00	104539.00	262721.50

Fig. 2. Investment costs for Situation (i).

4.2. *Illustrative example/Situation (ii)*

In this situation, it is cheaper for some plants, but not for all, to invest in prevention measures rather than to risk the costs and probabilities related to an internal domino effect. The difference with the previous example is that full cooperation would not have been the outcome of this game in case all plants played their individual Nash Equilibrium. This implies that, even though the all-invest outcome results in the lowest investment costs, it would not have been the outcome of the game without the presence of a Multi-Plant Council. This means that the sheer fact of gathering and assessing all required information enables the Multi-Plant Council to have all participating plants cooperating without the use of incentives. Hence, in such a situation no real financial incentives from the Multi-Plant Council are necessary in order to establish the (*I*, *I*, *I*, *I*, *I*)-situation, but merely *information incentives*. Let us assume the following direct annual investment costs:

Table 2
Potential losses and domino accident probabilities (DAP) for the illustrative examples.

DAP (times/year)	Plant A	Plant B	Plant C	Plant D	Plant E	Potential losses (€)
Plant A	1.10×10^{-4}	2.50×10^{-6}	3.40×10^{-6}	4.80×10^{-6}	0.90×10^{-6}	1.60×10^{8}
Plant B	2.30×10^{-6}	2.10×10^{-4}	4.30×10^{-6}	7.60×10^{-6}	8.80×10^{-6}	1.10×10^{8}
Plant C	6.50×10^{-6}	5.40×10^{-6}	3.80×10^{-4}	3.20×10^{-6}	1.20×10^{-6}	1.35×10^{8}
Plant D	6.60×10^{-6}	3.80×10^{-6}	7.60×10^{-6}	3.60×10^{-4}	2.20×10^{-6}	2.20×10^{8}
Plant E	8.10×10^{-6}	1.60×10^{-6}	2.50×10^{-6}	8.90×10^{-6}	7.50×10^{-4}	1.90×10^{8}

Direct investment cost:	
	Plant A: C_A = 21,000 €/year
	Plant B: C_B = 22,000 €/year
	Plant C: C_C = 53,000 €/year
	Plant D: C_D = 68,000 €/year
	Plant E: C_E = 103,000 €/year

Fig. 3 shows the total annual investment costs for every plant in all possible situations with the cross-plant information available to the MPC Data Administration. From these investment costs we can easily see that Plant A and Plant C will choose not to invest in prevention measures.

Plant A:	C_A = 21,000 €/year	>	$P_{A,A}L_A$ = 17,600 €/year
Plant C:	C_C = 53,000 €/year	>	$P_{B,B}L_B$ = 51,300 €/year

The As-Is situation that would result without the use of the *Multi-Plant Model* is therefore the strategic situation (*NI*, *I*, *NI*, *I*, *I*). Fig. 3 however shows that collaboration benefits are maximized in the all-invest situation (i.e. the To-Be situation).

It should be noted that for the calculation of collaboration benefits, internal as well as external domino effect costs are taken into account.

After calculating all investment costs, an analysis of the difference between the As-Is situation and the To-Be situation is performed, as shown in Table 3.

The deficits of Plant A and Plant C will be compensated by the surpluses of Plant B, Plant D and Plant E in a linear manner by the MPC.

Total Surplus (Plant B + Plant D + Plant E)	=€5863.97
Total Deficit (Plant A + Plant C)	=€3679.29
→**Difference** (Surplus – Deficit)	=€2184.68

- *Plant B* pays 12,38% (i.e. 726/5863,97) of the deficit of *Plant A* and *Plant C:*
  Compensation Plant B: €353.60 (i.e. 12.38% of €2856.12) to *Plant A*
  €101.91 (i.e. 12.38% of €823.17) to *Plant C*
- *Plant D* pays 53.27% (i.e. 3123.98/5863.97) of the deficit of *Plant A* and *Plant C:*
  Compensation Plant D: €1521.46 (i.e. 53.27% of €2856.12) to *Plant A*
  €438.50 (i.e. 53.27% of €823.17) to *Plant C*
- *Plant E* pays 34.35% (i.e. 2013.99/5863.97) of the deficit of *Plant A* and *Plant C*:
  Compensation Plant E: €981.08 (i.e. 34.35% of €2856.12) to *Plant A*
  €282.76 (i.e. 34.35% of €823.17) to *Plant C.*

Next, the remaining surplus of €2184.68 as a consequence of the maximization of collaboration benefits is linearly distributed to all the chemical plants in the cluster. This implies that each plant's investment cost is reduced by €436.94 (i.e. €2184.68/5). The annual investment costs of all plants in the To-Be situation can then be found in Table 4.

It is important to note that the use of the Multi-plant Collaboration Model in this situation minimizes the total investment costs for the cluster and therefore maximizes the collaboration benefits among the chemical plants. By distributing these benefits, every chemical plant in the cluster faces a lower (or at least an equal) annual investment cost in the To-Be-situation in comparison to the investment cost in the As-Is-situation.

In this example, the investment costs for plants A and C in the To Be situation (*17,706.94* €/year and *51,739.89* €/year, respectively) is still higher than the perceived maximum costs (*17,600* €/year and *51,300* €/year, respectively). However, as already mentioned, the *perceived costs* are merely used to identify in which strategic collaboration situation the cluster will find itself, based on perceptions by prevention management. In this case the situation would be (*NI*, *I*, *NI*, *I*, *I*). In that situation, the costs for plants A and C are calculated to be *18,143.88* €/year and *52,176.83* €/year, respectively, and thus higher than the investment costs in the To Be situation.

4.3. Illustrative example/Situation (iii)

In this case, it is cheaper for some but not for all plants to invest in prevention measures rather than risk initiating a domino effect. In this illustrative simulation, the direct investments cost of Plant B are significantly increased, resulting in a situation in which the all-invest strategy no longer minimizes the total investment costs for the cluster. Let us assume the following direct annual investment costs:

Direct investment cost:	
	Plant A: C_A = 21,000 €/year
	Plant B: C_B = 30,000 €/year
	Plant C: C_C = 53,000 €/year
	Plant D: C_D = 68,000 €/year
	Plant E: C_E = 103,000 €/year

The total annual investment costs for all plants as well as for the studied industrial area are given in Fig. 4. This figure indicates that the strategic situation (*I*, *NI*, *I*, *I*, *I*) minimizes the total investment costs for the cluster.

From Fig. 4, we can deduce that the As-Is situation would be the strategic situation (*NI*, *NI*, *NI*, *I*, *I*) since it is cheaper for Plant A, Plant B and Plant C to risk initiating a domino effect rather than to invest in prevention measures:

Plant A:	C_A = €23,000	>	$P_{A,A}L_A$ = €17,600
Plant B:	C_B = €30,000	>	$P_{B,B}L_B$ = €23,100
Plant C:	C_C = €53,000	>	$P_{C,C}L_C$ = €51,300

The To-Be situation in this example, as Fig. 4 shows, would be the strategic situation (*I*, *I*, *NI*, *I*, *I*). Table 5 shows the surpluses and deficits for all plants as a consequence of maximizing collaboration benefits.

The Multi-Plant Council will first use the surpluses of Plant B, Plant D and Plant E to compensate the deficits of Plant A and Plant C. Second, the additional collaboration benefits (i.e. €2183.69) are distributed linearly among the chemical plants. The resulting annual investment costs per plant are given in Table 6.

From Fig. 4 we can deduce that both Plant A and Plant C will not be persuaded to invest in prevention measures when facing the investment costs given in Table 6 since:

Plant A:	$u_A(NI, NI, I, I, I)$ = €17,999.91	<	$u_A(I, NI, I, I, I)^*$ = €18,107.05
Plant C:	$u_C(I, NI, NI, I, I)$ = €52,028.45	<	$u_C(I, NI, I, I, I)^*$ = €52,468.53

Therefore, an additional incentive of €107.14 (=€18,107.05 – €17,999.91) and an additional incentive of €440.08 (=€52,468.53 – €52,028.45) is necessary to shift Plant A respectively Plant C from the ‘not-invest’- to the ‘invest’-strategy. We propose that a Multi-Plant Council can obtain these incentives by means of collecting them from the other chemical plants in the cluster. We assume that these plants are willing to do this as long as they still benefit in comparison to the As-Is situation. Table 7 shows the total annual investment cost per plant as a consequence of fairly distributing collaboration benefits and additional incentives for Plant A and Plant C.

From Table 7 and Fig. 4 we can now deduce that every plant benefits as a consequence of the Multi-plant Collaboration Model:

Plant A:	$u_A(I, NI, I, I, I)^{**}$ = €17,999.91	≤	$u_A(NI, NI, I, I, I)$ = €17,999.91
Plant B:	$u_B(I, NI, I, I, I)^{**}$ = €23,571.36	≤	$u_B(I, I, I, I, I)$ = €30,000
Plant C:	$u_C(I, NI, I, I, I)^{**}$ = €52,028.45	≤	$u_C(I, NI, NI, I, I)$ = €52,028.45
Plant D:	$u_D(I, NI, I, I, I)^{**}$ = €71,705.62	≤	$u_D(I, NI, I, NI, I)$ = €80,035.40
Plant E:	$u_E(I, NI, I, I, I)^{**}$ = €105,063.66	≤	$u_E(I, NI, I, I, NI)$ = €142,803.54

According to the MCM model, the all-invest situation is not a feasible (rational) outcome in this situation. This example, however, demonstrates that a situation of partial cooperation can be induced, such that it becomes the end outcome. The all-invest situation would only be possible by means of external incentives (i.e. taxes or subsidies imposed or granted by authorities or insurance companies). In order to tip Plant B from the ‘not-invest’- to the ‘invest’-strategy, an external incentive of at least €6428.64 is needed.

Strategic situation	*Plant A*	*Plant B*	*Plant C*	*Plant D*	*Plant E*	Total Investment
(I, I, I, I, I)	**21000.00**	**22000.00**	**53000.00**	**68000.00**	**103000.00**	**267000.00**
(I, I, I, I, NI)	21144.00	22968.00	53162.00	68484.00	142500.00	308258.00
(I, I, I, NI, I)	21768.00	22836.00	53432.00	79200.00	104691.00	281927.00
(I, I, NI, I, I)	21544.00	22473.00	51300.00	69672.00	103475.00	268464.00
(I, NI, I, I, I)	21400.00	23100.00	53729.00	68836.00	103304.00	270369.00
(I, I, I, NI, NI)	21912.00	23803.99	53594.00	79683.65	144188.46	323182.10
(I, I, NI, I, NI)	21688.00	23440.99	51461.88	70155.99	142974.29	309721.15
(I, NI, I, I, NI)	21544.00	24067.59	53891.00	69320.00	142803.54	311626.13
(I, I, NI, NI, I)	22311.99	23308.99	51731.67	80870.80	105165.99	283389.45
(I, NI, I, NI, I)	22168.00	23935.65	54161.00	80035.40	104994.99	285295.03
(I, NI, NI, I, I)	21944.00	23572.80	52028.45	70507.99	103779.00	271832.23
(I, I, NI, NI, NI)	22455.99	24276.97	51893.55	81354.44	144662.74	324643.69
(I, NI, I, NI, NI)	22311.99	24903.23	54322.99	80519.05	144492.00	326549.26
(I, NI, NI, I, NI)	22088.00	24540.39	52190.32	70991.98	143277.83	313088.51
(I, NI, NI, NI, I)	22711.99	24408.44	52460.11	81706.18	105469.98	286756.71
(I, NI, NI, NI, NI)	22855.99	25376.01	52621.99	82189.82	144966.28	328010.09
(NI, NI, NI, NI, NI)	**19455.58**	**25628.90**	**53498.80**	**83640.74**	**146502.93**	**328726.94**
(NI, NI, NI, NI, I)	19311.61	24661.33	53336.93	83157.10	107008.94	287475.92
(NI, NI, NI, I, NI)	18687.76	24793.27	53067.14	72443.94	144814.51	313806.62
(NI, NI, I, NI, NI)	18911.71	25156.11	55200.48	81969.98	146028.66	327266.94
(NI, I, NI, NI, NI)	19055.67	24529.96	52770.37	82805.37	146199.40	325360.77
(NI, NI, NI, I, I)	18543.79	23825.69	52905.27	71959.95	105317.99	272552.69
(NI, NI, I, NI, I)	18767.74	24188.54	55038.48	81486.34	106533.96	286015.06
(NI, I, NI, NI, I)	18911.71	23561.99	52608.50	82321.73	106704.96	284108.88
(NI, NI, I, I, NI)	18143.88	24320.48	54768.49	70771.98	144340.23	312345.06
(NI, I, NI, I, NI)	18287.85	23693.99	52338.71	71607.96	144510.97	310439.48
(NI, I, I, NI, NI)	18511.80	24056.98	54471.49	81134.60	145725.13	323899.99
(NI, NI, I, I, I)	17999.91	23352.89	54606.49	70287.99	104843.00	271090.28
(NI, I, NI, I, I)	18143.88	22726.00	52176.83	71123.98	105013.99	269184.68
(NI, I, I, NI, I)	18367.83	23089.00	54309.49	80650.95	106229.97	282647.25
(NI, I, I, I, NI)	17743.97	23221.00	54039.50	69935.99	144036.69	308977.15
(NI, I, I, I, I)	17600.00	22253.00	53877.50	69452.00	104539.00	267721.50

Fig. 3. Investment costs for Situation (ii).

Table 3
Surplus (+) and Deficit (−) per plant in Situation (ii).

Strategic situation	Plant A	Plant B	Plant C	Plant D	Plant E	Total investment
(*NI, I, NI, I, I*)	18,143.88	22,726.00	52,176.83	71,123.98	105,013.99	269,184.68
(*I, I, I, I, I*)	21,000.00	22,000.00	53,000.00	68,000.00	103,000.00	267,000.00
Surplus/Deficit:	−2856.12	+726.00	−823.17	+3123.98	+2013.99	+2184.68

Table 4
Total annual investment costs per plant in Situation (ii).

Strategic situation	Plant A	Plant B	Plant C	Plant D	Plant E	Total investment
(*I, I, I, I, I*)*	17,706.94	22,289.06	51,739.89	70,687.04	104,577.05	267,000.00

Table 5
Surplus (+) and Deficit (−) per plant in Situation (iii).

Strategic situation	Plant A	Plant B	Plant C	Plant D	Plant E	Total investment
(*NI, NI, NI, I, I*)	18,543.79	23,825.69	52,905.27	71,959.95	105,317.99	272,552.69
(*I, NI, I, I, I*)	21,400.00	23,100.00	53,729.00	68,836.00	103,304.00	270,369.00
Surplus/Deficit	−2856.21	+725.69	−823.73	+3123.95	+2013.99	+2183.69

Strategic Situations	Plant A	Plant B	Plant C	Plant D	Plant E	Total Investment
(I, I, I, I, I)	21000.00	30000.00	53000.00	68000.00	103000.00	275000.00
(I, I, I, I, NI)	21144.00	30968.00	53162.00	68484.00	142500.00	316258.00
(I, I, I, NI, I)	21768.00	30836.00	53432.00	79200.00	104691.00	289927.00
(I, I, NI, I, I)	21544.00	30473.00	51300.00	69672.00	103475.00	276464.00
(I, NI, I, I, I)	21400.00	23100.00	53729.00	68836.00	103304.00	270369.00
(I, I, I, NI, NI)	21912.00	31803.99	53594.00	79683.65	144188.46	331182.10
(I, I, NI, I, NI)	21688.00	31440.99	51461.88	70155.99	142974.29	317721.15
(I, NI, I, I, NI)	21544.00	24067.59	53891.00	69320.00	142803.54	311626.13
(I, I, NI, NI, I)	22311.99	31308.99	51731.67	80870.80	105165.99	291389.45
(I, NI, I, NI, I)	22168.00	23935.65	54161.00	80035.40	104994.99	285295.03
(I, NI, NI, I, I)	21944.00	23572.80	52028.45	70507.99	103779.00	271832.23
(I, I, NI, NI, NI)	22455.99	32276.97	51893.55	81354.44	144662.74	332643.69
(I, NI, I, NI, NI)	22311.99	24903.23	54322.99	80519.05	144492.00	326549.26
(I, NI, NI, I, NI)	22088.00	24540.39	52190.32	70991.98	143277.83	313088.51
(I, NI, NI, NI, I)	22711.99	24408.44	52460.11	81706.18	105469.98	286756.71
(I, NI, NI, NI, NI)	22855.99	25376.01	52621.99	82189.82	144966.28	328010.09
(NI, NI, NI, NI, NI)	19455.58	25628.90	53498.80	83640.74	146502.93	328726.94
(NI, NI, NI, NI, I)	19311.61	24661.33	53336.93	83157.10	107008.94	287475.92
(NI, NI, NI, I, NI)	18687.76	24793.27	53067.14	72443.94	144814.51	313806.62
(NI, NI, I, NI, NI)	18911.71	25156.11	55200.48	81969.98	146028.66	327266.94
(NI, I, NI, NI, NI)	19055.67	32529.96	52770.37	82805.37	146199.40	333360.77
(NI, NI, NI, I, I)	18543.79	23825.69	52905.27	71959.95	105317.99	272552.69
(NI, NI, I, NI, I)	18767.74	24188.54	55038.48	81486.34	106533.96	286015.06
(NI, I, NI, NI, I)	18911.71	31561.99	52608.50	82321.73	106704.96	292108.88
(NI, NI, I, I, NI)	18143.88	24320.48	54768.49	70771.98	144340.23	312345.06
(NI, I, NI, I, NI)	18287.85	31693.99	52338.71	71607.96	144510.97	318439.48
(NI, I, I, NI, NI)	18511.80	32056.98	54471.49	81134.60	145725.13	331899.99
(NI, NI, I, I, I)	17999.91	23352.89	54606.49	70287.99	104843.00	271090.28
(NI, I, NI, I, I)	18143.88	30726.00	52176.83	71123.98	105013.99	277184.68
(NI, I, I, NI, I)	18367.83	31089.00	54309.49	80650.95	106229.97	290647.25
(NI, I, I, I, NI)	17743.97	31221.00	54039.50	69935.99	144036.69	316977.15
(NI, I, I, I, I)	17600.00	30253.00	53877.50	69452.00	104539.00	275721.50

Fig. 4. Investment costs for Situation (iii).

Table 6
Investment costs per plant in strategic situation (*I, NI, I, I, I*)*.

Strategic situation	Plant A	Plant B	Plant C	Plant D	Plant E	Total investment
(*I, NI, I, I, I*)*	18,107.05	23,388.95	52,468.53	71,523.21	104,881.25	270,369.00

Table 7
Investment costs per plant in the To-Be situation.

Strategic situation	Plant A	Plant B	Plant C	Plant D	Plant E	Total investment
(*I, NI, I, I, I*)**	17,999.91	23,571.36	52,028.45	71,705.62	105,063.66	270,369.00

Subsidy or incurance fee reduction: *Plant B:* $S_B \geq (C_B - P_{B,B}L_B)$
$S_B \geq$ €6428.64
(=(€30,000 – €23,571.36))

Tax or insurance fee increase: *Plant B:* $C_B \leq (T_B + P_{B,B}L_B)$
€30,000 ≤ (T_B + €23,571.36)

4.4. Illustrative example/Situation (iv)

In this example, it is individually cheaper for all plants not to invest in domino effect prevention measures. We assume the

Strategic Situation	*Plant A*	*Plant B*	*Plant C*	*Plant D*	*Plant E*	Total Investment
(I, I, I, I, I)	20000.00	25000.00	53000.00	81000.00	144000.00	**323000.00**
(I, I, I, I, NI)	20144.00	25968.00	53162.00	81484.00	142500.00	323258.00
(I, I, I, NI, I)	20768.00	25836.00	53432.00	79200.00	145691.00	324927.00
(I, I, NI, I, I)	20544.00	25473.00	51300.00	82672.00	144475.00	324464.00
(I, NI, I, I, I)	20400.00	23100.00	53729.00	81836.00	144304.00	323369.00
(I, I, I, NI, NI)	20912.00	26803.99	53594.00	79683.65	144188.46	325182.10
(I, I, NI, I, NI)	20688.00	26440.99	51461.88	83155.99	142974.29	324721.15
(I, NI, I, I, NI)	20544.00	24067.59	53891.00	82320.00	142803.54	323626.13
(I, I, NI, NI, I)	21311.99	26308.99	51731.67	80870.80	146165.99	326389.45
(I, NI, I, NI, I)	21168.00	23935.65	54161.00	80035.40	145994.99	325295.03
(I, NI, NI, I, I)	20944.00	23572.80	52028.45	83507.99	144779.00	324832.23
(I, I, NI, NI, NI)	21455.99	27276.97	51893.55	81354.44	144662.74	326643.69
(I, NI, I, NI, NI)	21311.99	24903.23	54322.99	80519.05	144492.00	325549.26
(I, NI, NI, I, NI)	21088.00	24540.39	52190.32	83991.98	143277.83	325088.51
(I, NI, NI, NI, I)	21711.99	24408.44	52460.11	81706.18	146469.98	326756.71
(I, NI, NI, NI, NI)	21855.99	25376.01	52621.99	82189.82	144966.28	327010.09
(NI, NI, NI, NI, NI)	19455.58	25628.90	53498.80	83640.74	146502.93	328726.94
(NI, NI, NI, NI, I)	19311.61	24661.33	53336.93	83157.10	148008.94	328475.92
(NI, NI, NI, I, NI)	18687.76	24793.27	53067.14	85443.94	144814.51	326806.62
(NI, NI, I, NI, NI)	18911.71	25156.11	55200.48	81969.98	146028.66	327266.94
(NI, I, NI, NI, NI)	19055.67	27529.96	52770.37	82805.37	146199.40	328360.77
(NI, NI, NI, I, I)	18543.79	23825.69	52905.27	84959.95	146317.99	326552.69
(NI, NI, I, NI, I)	18767.74	24188.54	55038.48	81486.34	147533.96	327015.06
(NI, I, NI, NI, I)	18911.71	26561.99	52608.50	82321.73	147704.96	328108.88
(NI, NI, I, I, NI)	18143.88	24320.48	54768.49	83771.98	144340.23	325345.06
(NI, I, NI, I, NI)	18287.85	26693.99	52338.71	84607.96	144510.97	326439.48
(NI, I, I, NI, NI)	18511.80	27056.98	54471.49	81134.60	145725.13	326899.99
(NI, NI, I, I, I)	17999.91	23352.89	54606.49	83287.99	145843.00	325090.28
(NI, I, NI, I, I)	18143.88	25726.00	52176.83	84123.98	146013.99	326184.68
(NI, I, I, NI, I)	18367.83	26089.00	54309.49	80650.95	147229.97	326647.25
(NI, I, I, I, NI)	17743.97	26221.00	54039.50	82935.99	144036.69	324977.15
(NI, I, I, I, I)	17600.00	25253.00	53877.50	82452.00	145539.00	324721.50

Fig. 5. Investment costs per plant in Situation (iv).

following investment costs and compare them to the implicit impact costs.

Plant A:	$C_A = 20{,}000$ €/year	>	$P_{A,A}L_A = 17{,}600$ €/year
Plant B:	$C_B = 25{,}000$ €/year	>	$P_{B,B}L_B = 23{,}100$ €/year
Plant C:	$C_C = 53{,}000$ €/year	>	$P_{C,C}L_C = 51{,}300$ €/year
Plant D:	$C_D = 81{,}000$ €/year	>	$P_{D,D}L_D = 79{,}200$ €/year
Plant E:	$C_E = 144{,}000$ €/year	>	$P_{E,E}L_E = 142{,}500$ €/year

As a consequence, we know that the resulting As-Is situation is equal to a situation in which no plant cooperates (i.e. strategic situation (*NI*, *NI*, *NI*, *NI*, *NI*)). From Fig. 5, we can conclude that the investment cost on a cluster level is minimized in the all-invest situation (i.e. the To-Be situation).

After compensating all losing plants with the surpluses of all winning plants in the To-Be situation and after distributing all additional collaboration benefits, we find the investment costs as displayed in Table 8.

Consequently, let us assess whether all plants are persuaded to invest in prevention measures.

Plant A: $u_A(NI, NI, NI, NI, NI)^*$	=€18,310.19	<	$u_A(I, NI, NI, NI, NI)$ = €21,855.99
Plant B: $u_B(NI, NI, NI, NI, NI)^*$	=€24,483.51	<	$u_B(NI, I, NI, NI, NI)$ = €27,529.96
Plant C: $u_C(NI, NI, NI, NI, NI)^*$	=€52,353.41	<	$u_C(NI, NI, I, NI, NI)$ = €55,200.48
Plant D: $u_D(NI, NI, NI, NI, NI)^*$	=€82,495.35	<	$u_D(NI, NI, NI, I, NI)$ = €85,443.94
Plant E: $u_E(NI, NI, NI, NI, NI)^*$	=€145,357.54	<	$u_E(NI, NI, NI, NI, I)$ = €148,008.94

Hence, none of the plants is persuaded to invest in prevention measures after distributing the collaboration benefits. It is essential to note that in this situation, it is impossible by the Multi-plant Collaboration Model to persuade all chemical plants without the use of external incentives. In order to calculate the amount of external incentives necessary to tip all chemical plants, we need to compare the investment costs in the As-Is situation (i.e. without the realization of collaboration benefits since they do not occur in this example) with the investment costs necessary to tip each plant individually.

Table 8
Investment costs per plant in strategic situation (*NI*, *NI*, *NI*, *NI*, *NI*)*.

Strategic situation	Plant A	Plant B	Plant C	Plant D	Plant E	Total investment
(*NI*, *NI*, *NI*, *NI*, *NI*)*	18,310.19	24,483.51	52,353.41	82,495.35	145,357.54	323,000.00

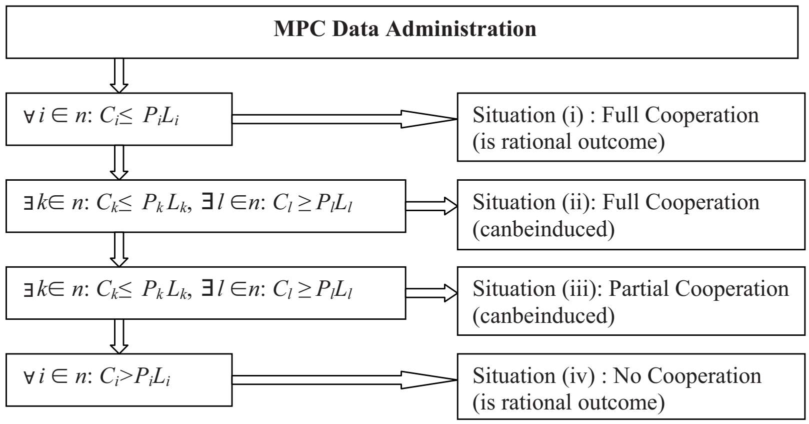

Fig. 6. Approach for the Multi-plant Collaboration Model.

Plant A: u_A(*NI*, *NI*, *NI*, *NI*, *NI*)	=€19,455.58	<	u_A(*I*, *NI*, *NI*, *NI*, *NI*) = €21,855.99
Plant B: u_B(*NI*, *NI*, *NI*, *NI*, *NI*)	=€25,628.90	<	u_B(NI, I, NI, NI, NI) = €27,529.96
Plant C: u_C(*NI*, *NI*, *NI*, *NI*, *NI*)	=€53,498.80	<	u_C(*NI*, *NI*, *I*, *NI*, *NI*) = €55,200.48
Plant D: u_D(*NI*, *NI*, *NI*, *NI*, *NI*)	=€83,640.74	<	u_D(*NI*, *NI*, *NI*, *I*, *NI*) = €85,443.94
Plant E: u_E(*NI*, *NI*, *NI*, *NI*, *NI*)	=€146,502.93	<	u_E(*NI*, *NI*, *NI*, *NI*, *I*) = €148,008.94

The external incentive necessary to tip every plant individually then is:

Plant A:	$S_A = T_A$ = (€21,855.99 – €19,455.58)	=€2400.41
Plant B:	$S_B = T_B$ = (€27,529.96 – €25,628.90)	=€1901.06
Plant C:	$S_C = T_C$ = (€55,200.48 – €53,498.80)	=€1701.68
Plant D:	$S_D = T_D$ = (€85,443.94 – €83,640.74)	=€1803.20
Plant E:	$S_E = T_E$ = (€148,008.94 – €146,502.93)	=€1506.01
Total amount of external subsidies:		**=€9312.36**

In this situation, the all-invest situation is not a feasible outcome since we cannot guarantee that the chemical plants obtain these external incentives. The outcome according to the MCM is therefore a situation in which none of the plants decides to invest in prevention measures (i.e. strategic situation (*NI*, *NI*, *NI*, *NI*, *NI*)).

5. Discussion

The primary goal of the Multi-plant Collaboration Model is to stimulate cooperation among a cluster of chemical plants in order to reduce the likelihood and the consequences of a domino effect occurring within the industrial area. A supra-plant body, called the Multi-Plant Council, stimulates cooperation through realizing collaboration benefits. Since a Multi-Plant Council does not exist in current industrial practice, we assume that such a body, would it be created, would not have any budget at its disposal (at least at first instance). The illustrative examples of the previous section show how, by means of the proposed Multi-plant Collaboration Model, collaboration with regard to domino effect prevention can be stimulated among chemical plants. However, as Fig. 6 shows, the MCM has only limited power to stimulate collaboration on the one hand and realize collaboration benefits on the other hand. The MPC Data Administration's starting point for realizing collaboration benefits is the difference in investment costs between the As-Is situation (i.e. the strategic situation that would result without the use of the MCM) and the To-Be situation for all plants. The investment costs in the As-Is situation result from the fact whether prevention management perceives it less costly to invest in domino effect prevention rather than risking the costs and probabilities of an internal domino effect. Since prevention management cannot influence the strategy choices of the other prevention managers, they can only base their decision whether or not to invest on the difference in cost between investing (with a resulting investment cost C_i) and not investing (with a resulting implicit cost P_iL_i).

In Situation (i) it is less costly for every plant to invest in domino effect prevention rather than risking an internal domino effect. Therefore, the outcome of the MCM (i.e. the strategic situation that maximizes the collaboration benefits) is a situation of full cooperation. It is, however, important to note that this situation would also have been the outcome without the use of MCM. In a chemical cluster, it is not guaranteed that $C_i \leq P_iL_i$.

Situation (ii), in turn, shows that by means of the MCM full cooperation is possible even though it is not for every plant in the cluster less costly to invest in domino effect prevention. However, Situation (iii) shows that it is possible that full cooperation not always maximizes the collaboration benefits of the chemical cluster in a situation where it is not for all plants less costly to invest in domino effect prevention. Situation (iv) shows that without the use of external incentives the MCM cannot always stimulate cooperation. If it is for every plant more expensive to invest in domino effect prevention than not invest, a situation of no cooperation is the only possible outcome in the MCM.

6. Conclusions

In this paper, a Multi-plant Collaboration Model is elaborated for stimulating cooperation across possibly competing chemical plants in an industrial area. It should be stressed that some important simplifying assumptions were made in the model. First, decision-makers are assumed to be risk-neutral. Second, domino effects, if they occur, are assumed to have disastrous consequences, destroying entire plants. Third, prevention measures against domino effects are assumed to be fully effective and completely protect against such accidents. Obviously, these assumptions give an indication about possible future research to be carried out to lower the model's limitations. Since we also assume that company prevention management has limited knowledge about other plants' strategies, it solely bases its cross-plant prevention decisions on their own preferences and on the perceptions they have about the preferences of other plants' prevention management. It turns out that prevention management let its decisions be directed by the simple fact whether or not it is more or less expensive to invest in prevention measures than to not invest in such measures and to face potential internal domino effect losses. Confidentiality issues are solved in the model by having a supra-plant body, called the Multi-Plant Council, processing cross-company information. Since the MPC disposes of all required data of every plant, it can calculate the annual investment costs for all plants in all strategic cooperative situations. By doing so, the strategic collaborative situation of the cluster minimizing the total annual investment costs, or in other words maximizing the collaboration benefits, is determined. In fact, cooperation benefits might not always lead to an *all-invest* situation. External incentives such as subsidies or taxes granted or imposed by external parties such as authorities or insurance companies may indeed be needed to shift plants from not investing towards investing.

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