

A domino effect evaluation model.

Abstract

This paper makes an original contribution towards managing knock-on major accidents or accidents caused by so-called domino effects by presenting a 5 step evaluation model. First, a ‘domino danger unit’ for every couple installations in a complex network consisting of chemical installations is calculated. Second, an enumerative approach for the relative ranking of domino effects sequences between types of installations and for different accident scenarios and dangerous substances is worked out. Third, a ‘Segment Risk Factor’ is calculated by considering the frequency of the domino path segment and the overall danger of the path segment towards domino accidents. Finally, an overall classification of domino path sequences is made in order of decreasing danger. Such a classification of domino effects sequences can be implemented by safety management as a tool to support decisions on prevention prioritization.

1. Introduction

In Europe, the basic guidelines for preventing major accidents¹ are stipulated in the Seveso 1996 Directive [1]. Article 8 of this so-called Seveso II Directive uses the term *domino effects* to denote the existence of “*establishments or groups of establishments where the likelihood and the possibility or consequences of a major accident may be increased because of the location and the proximity of such establishments, and their inventories of dangerous substances*”. Present safety research has lead to a variety of methodologies to assess the significance of domino effects from major hazard sites. Factors relevant to domino escalation and various direct and indirect mechanisms for obtaining a domino accident (caused by domino

¹ The definition of *major accident* within the European Directive 96/82/EG is ‘an occurrence such as a major emission, fire, or explosion resulting from uncontrolled developments in the course of the operation of any establishment covered by the Directive, and leading to serious danger to human health and/or the environment, immediate or delayed, inside or outside the establishment, and involving one or more dangerous substances’.

effects) have been determined. However, Atkins (1998) [2] shows that an overall coherent approach for prevention optimization of cascade accident risks in a chemical industrial complex does not exist. Recent empirical research in the Antwerp port area (2004) [3] indicates that this situation has not changed since 1998. Moreover, no well accepted methodologies are available in the literature for the assessment of domino hazards (Cozzani *et al.*, 2001, [4]).

Domino safety research is most often supported by government and mainly focuses on identifying potential domino effects and determining their overall impact on the accident area. In fact, investigating domino effects in present safety tools covers the potential for domino effect consequences between plant items on the same site (internal domino effects) or those on different sites or between a petrochemical plant and the community (external domino effects). Often, mathematical models for the simulation of domino accidents are demanding due to the complexity of the accident evolution (simulation of the source term, ignition, non-ignition, delayed ignition, dense vapour, buoyant vapour,...) and to the complexity of the input data required. Nevertheless, several software packages have been developed on identifying potential domino effects.

In Italy, an area risk assessment study called ARIPAR has been carried out before the regulations stated in the Seveso II Directive (Egidi *et al.*, 1995 [5]). The original methodology and algorithm of the program has been modified and in 2003 the latest version has been proposed. ARIPAR version 3.0 implements a probabilistic methodology for the assessment of the risks of complex industrial areas, including transport of dangerous substances, to obtain a number of different risk measures (Spadoni, 2003 [6]).

STARS Domino (Software Toolkit for Advanced Reliability and Safety analysis Domino) is an integrated software package composed of four modules: Knowledge Base, System Model, Fault Tree and Event Tree. As explained by Ballocco (2000) [7], a consequence assessment is carried out by constructing an accidental scenario and simulating phenomenological events using the Event Tree as a reference module. In this module, tools are available to create an event tree and execute external calculation models.

DISMA (DISaster MAnagement) is a tool designed for implementing the Seveso II Directive. Uth (1999) [8] shows the multi-use of the program, suitable for Safety Report scenario building, in-site and off-site emergency planning, domino effect calculation and land-use planning.

The SHELL SHEPHERD Software is an example of a commercial developed safety toolkit allowing users, among other things, to examine escalation and domino effects [9].

DOMIFFECT (DOMIno eFFECT) is a software tool developed by Khan and Abbasi (1998a) [10] for domino effect analysis in chemical process industries and is based on deterministic models used in conjunction with probabilistic analysis. The tool is based on a systematic domino method, Domino Effect Analysis (DEA), also developed by Khan and Abbasi (1998b) [11]. Research conducted by the DEA authors indicate, among other things, that it is not necessary that the unit of an industry which may cause the biggest stand-alone accident will also be the one most likely to cause a domino effect (2001) [12].

DOMINOXL 2.0 (Delvosalle *et al.*, 2002) [13] enumerates all possible domino effects that can lead to internal and external domino accidents. Subsequently, the most dangerous equipment zones or pipes for a given scenario² in a group of chemical plants are determined by adding up the number of primary domino effects per installation³, leading to a Dangerousness Factor (*DF*). Analogous, also the most vulnerable equipment zones or pipes are determined by adding up the number of domino effects for which the installation, then considered as a secondary installation⁴, is reached for a given protection level. This calculation leads to a Vulnerability Factor (*VF*). Both *DF* and *VF* are calculated taking into account a weighting coefficient defined by the user.

None of the existing methods is able to give information on the unidirectional danger between two installations in a chemical surrounding and use it for determining

² Accident scenarios are: a Vapour Cloud Explosion (VCE), a Poolfire, a Jetfire, a Tankfire, a Boilover, a Boiling Liquid Expanding Vapor Explosion (BLEVE), an Explosion with projectile emission.

³ An installation is a technical unit within an establishment in which dangerous substances are produced, used, handled or stored. It shall include all the equipment, structures, pipework, machinery, tools, private railway sidings, docks, unloading quays serving the installation, jetties, warehouses or similar structures, floating or otherwise, necessary for the operation of the installation.

⁴ A secondary installation is hit by a domino effect, and fails as a result. A primary installation causes a domino effect.

possible accident paths constituted by domino effects. To determine whether an unwanted event occurring at installation i is likely to give rise to an unwanted event at installation j , it is necessary to consider the magnitude of the occurrence at installation i , the likelihood that this event will cause damage at installation j and the level of damage to be expected at installation j . Based on these factors, unidirectional danger factors expressing the amount of danger from one individual installation to another can be calculated. In this paper, they are referred to as Domino Danger Units (DDU) and are used to develop a procedure to evaluate domino effects paths. Such an approach for developing a systematic domino path evaluation procedure leading to optimizing prevention information on the level of every single installation has -to the best of our knowledge- not yet been practiced.

The proposed method performs a domino danger paths ranking, producing easy to understand information that can immediately be put into practice. The obtained data facilitates making objective choices about the location for the implementation of precaution measures to avoid major accidents in an industrial area.

2. Definitions and Notation

2.1. Domino effects definition

To build such a method, the concept of domino effects has to be well defined. Although there is no generally accepted definition of what constitute domino effects, various authors have provided suggestions. Table 1.1 presents an overview of current definitions identified in a review of relevant documents.

Table 1.1 Current Domino Effect Definitions.

<i>Author</i>	<i>Domino effect Definition</i>
Lees [14]	A factor to take account of the hazard that can occur if leakage of a hazardous material can lead to the escalation of the incident, e.g. a small leak which fires and damages by flame impingement a larger pipe or vessel with subsequent spillage of a large inventory of hazardous material.
Bagster and Pitblado [15]	A loss of containment of a plant item which results from a serious incident on a nearby plant unit.
Third Report of the Advisory Committee on Major Hazards [16]	The effects of major accidents on other plants on the site or nearby sites.
Delvosalle [17]	A cascade of events in which the consequences of a previous accident are increased by following one(s), spatially as well as temporally, leading to a major accident.

The generalized definition provided by Delvosalle (1996) has the advantage of allowing for the introduction of a mathematical approach of domino accident optimization problems. According to this definition, a domino effect implies a primary accident concerning a primary installation (this event might not be a major accident), inducing one (or more) secondary accident(s), concerning secondary installation(s). This (these) secondary accident(s) must be major one(s) and must extend the damages of the primary accident. Thus, domino effects act in a chain, involving a number of installations. Consequently, each installation represents a direct (or an indirect) threat to every other installation in a chemical industrial area. Every installation in such an industrial area can be represented as a node in a directed network of chemical installations. All nodes are connected by a pair of unidirectional arcs. By using Domino Danger Units as weights on the arcs, the amount of danger from one installation to another is expressed. All possible sequences of two adjacent arcs in a complex installations network are analyzed.

2.2. Domino effects categorization

For better understanding and for defining the Domino Effect Evaluation problem, it is useful to categorize domino effects into the various types that may occur. Four different parameters are used to unambiguously identify the character of the domino

effect under consideration. The various domino effects characters are explained in Table 1.2.

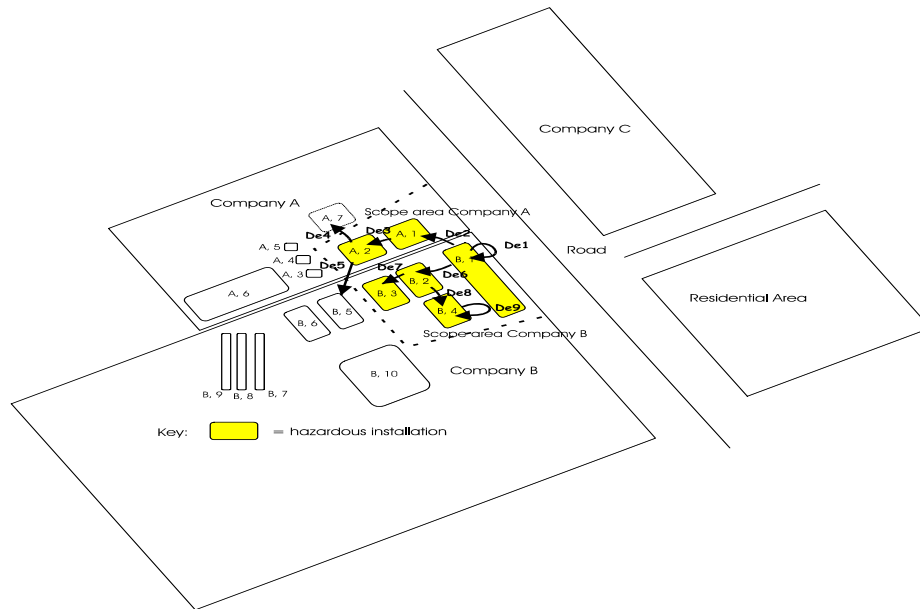
Table 1.2 Categorization of domino effects.

<i>CATEGORIZATION OF DOMINO EFFECTS</i>		
<u>CHARACTER:</u>	<u>INSTANCES OF CHARACTER:</u>	<u>DEFINITION OF CHARACTER:</u>
CHARACTER 1:	Internal	Happening inside the boundaries of the plant where the domino accident originates.
	External	Happening outside the boundaries of the plant where the domino accident originates, as a direct or an indirect result.
CHARACTER 2:	Direct	Happening as a direct consequence of the previous domino event.
	Indirect	Happening as an indirect consequence of a preceding domino event, not being the previous one.
CHARACTER 3:	Temporal	Happening within the same area as the preceding event, but with a delay.
	Spatial	Happening outside the area where the preceding event took place, with or without a delay.
CHARACTER 4:	Serial	Happening as a consequent link of the only accident chain caused by the preceding event.
	Parallel	Happening as one of several simultaneous consequent links of accident chains caused by the preceding event.

From the definitions of a *direct or indirect domino effect*, it is not possible to deduce how many domino effects have happened before the effect under consideration. For this purpose, we can introduce the concept of *domino cardinality*, a term used to indicate the domino effect link number in a sequence of domino effects, starting from the initiating event, numbered ‘0’.

These categorizing definitions are illustrated by considering a hypothetical domino accident providing a good overview of the different aspects of domino effects (see Figure 1.1).

Figure 1.1 Hypothetical domino accident illustrating the domino effects complexity.



Let us consider installation B.1 of company B in Figure 1.1 as the lift-off of the domino accident (e.g. assume a gas leak), thus being the origin of the domino event, having cardinality zero. As a result, a minor incident develops hypothetically into an escalation accident the following way. The gas leak gives rise to a gas cloud inside installation B.1. At a certain moment, the leaking gas cloud gets ignited, resulting in a poolfire (De1, temporal) and in a BLEVE (De6, spatial) producing a fireball and missiles. The radiation caused by the poolfire results 15 minutes later in another BLEVE (De2, spatial) affecting an installation unit (A.1) situated on the premises of a nearby plant A. The De6-BLEVE causes a major fire in a nearby unit B.2, and as a result of heavy overheating the installation items B.3 and B.4 are severely damaged at approximately the same time (De7 and De8). A heat-resulting flashfire (De9) in installation B.4 destroys half the installation within the hour. The De2-BLEVE causes several fires in installation A.1, in turn leading to a classic BLEVE mode by overheating (De3). Due to De3, another installation (A.2) of company A gives rise to fireballs (BLEVEs) causing minor damage to installations A.7 (De4) and B.5 (De5). The different exemplary domino effects can then be categorized as in Table 1.3.

Table 1.3 Character of the hypothetical exemplary domino effects depicted in Figure 1.1

<i>Character</i>		<i>De1</i>	<i>De2</i>	<i>De3</i>	<i>De4</i>	<i>De5</i>	<i>De6</i>	<i>De7</i>	<i>De8</i>	<i>De9</i>
1	Internal									
	External									
2a	Direct									
	Indirect									
2b	Cardinality	1	2	3	4	4	1	2	2	3
3	Temporal									
	Spatial									
4	Serial									
	Parallel									

In this paper, domino effects are considered to be serial. This constraint has no influence on the study's results, because the calculated unidirectional danger units between the installations express the simultaneously existing danger between each and every installation. Hence, if, for example, two installations are to be hit at the same time, two danger paths are calculated each with its own danger path factor.

2.3. Graphs and paths

Let $G = (N, A)$ denote a graph of a given network. The network consists of a set of nodes $N = \{v_1, \dots, v_n\}$ (e.g. representing chemical installations) and a set of arcs $A = \{a_1, \dots, a_m\} \subset N \times N$. Each arc a_k denotes a pair of nodes (v_i, v_j) , with $v_i \neq v_j$. It is assumed that $1 \leq N < \infty$ and $0 \leq A < \infty$. The arc (v_i, v_j) is said to be an ordered pair of nodes if it is to be distinguished from the pair (v_j, v_i) . If $\forall (v_i, v_j) \in A$ is ordered, (N, A) is called a directed network. In what follows, the network is assumed to be directed.

Let s and t be two nodes of (N, A) . A path p from s to t in (N, A) is an alternating sequence of nodes and arcs of the form $p = \langle v'_1, a'_1, v'_2, \dots, v'_l, a'_l, v'_{l+1} \rangle$, such that:

- $v'_i \in N, \forall i \in \{1, \dots, l+1\}$;
- $a'_k = (v'_k, v'_{k+1}) \in A, \forall k \in \{1, \dots, l\}$;
- $v'_1 = s$ and $v'_{l+1} = t$

Nodes s and t are respectively called the start node and terminal node of path p . The arc (v'_i, v'_{i+1}) is outgoing from node v'_i and incoming to node v'_{i+1} . Only one arc is allowed between a pair of nodes in the same direction.

A cycle or loop in (N, A) is a path p from one node to itself where all other nodes except s and t are different (that is, $s = t$). A path is said to be loopless *if and only if* all its nodes are different. A null path is a sequence with a single node. In the Domino Effects Evaluation problem loopless paths are assumed.

p_{ij} denotes the path in G from node v_i to node v_j . Given two nodes x and y of a path p_{ij} , $seg_{xy}^{p_{ij}}$ is defined as a segment of path p_{ij} if it coincides with p_{ij} from x until y .

In many applications involving graphs, it is useful to introduce a variable that measures the weight of each arc, like for example, the arc cost or the arc distance. In this paper, the weight of an arc (v_i, v_j) with $v_i \neq v_j$ represents the amount of danger outgoing from installation i onto installation j . Mathematically, the arc weight is simply a scalar (real number) referred to as the Domino Danger Unit (DDU). Let DDU_{ij} denote the weight of an arc (v_i, v_j) with $v_i \neq v_j$, such that:

- $DDU_{ij} \in R^+, \forall i \neq j$;
- $DDU_{ij} = 0$ if $i = j$.

By calculating all (unidirectional) Domino Danger Units between all nodes in the entire network we can obtain an installations square danger matrix DDU of order $n \times n$:

$$DDU = \begin{bmatrix} 0 & DDU_{12} & \dots & DDU_{1n} \\ DDU_{21} & 0 & & \\ \dots & & 0 & \dots \\ & & & 0 \\ DDU_{n1} & \dots & & 0 \end{bmatrix}$$

2.4. Probability of domino events (P^j)

A formula for calculating the probability of a domino event initiated by a particular installation j situated in a surrounding of $(N-1)$ installation items must be derived. Let the factor $P_{i,j}$ represent the probability that a domino event will occur on equipment i

(being considered in isolation) caused by a *direct domino effect* from installation j . If there are $(N-1)$ installation items that could be affected by the primary failure of installation item j , then it is necessary to avoid double counting, i.e. taking into account a domino effect occurring on a plant item when it has already occurred on other plant items. This double counting would arise if the probabilities $P_{1,j}$ to $P_{N-1,j}$ be simply added to give the overall probability of a domino accident, thus ignoring the cross products and possibly leading to a probability value of more than 1.

More precisely, assume a network consisting of 4 chemical installations: A , B , C and D . Let A be the initiating installation item. If $P_{B,A}$ is the probability of a domino event occurring on equipment B if it is considered in isolation given that the primary event on A has occurred, then the assumption is made that it is not possible for an event occurring on C and/or D at the same time because only serial domino effects are considered. Hence, the probability of A causing a direct domino event in the network can not be calculated in an easy way by summing $P_{B,A}$, $P_{C,A}$ and $P_{D,A}$.

To avoid calculating the cross products explicitly, it is possible to convert to probability of the success state (i.e. the probability of a domino event not arising as a result of primary failure of equipment j on item i can be expressed as $1 - P_{i,j}$). If terms for each of the $(N-1)$ installations are calculated and are multiplied, then the probability of a domino event not arising as a result of primary failure of equipment j on items 1 to $(N-1)$ becomes

$$\prod_{i=1}^{N-1} (1 - P_{i,j}) \quad (1)$$

The probability of a domino accident arising from installation j in a network of N chemical installations (including j) is thus

$$P^j = 1 - \prod_{i=1}^{N-1} (1 - P_{i,j}) \quad (2)$$

This expression (2) gives the overall probability of a domino accident occurring from a particular installation item.

2.5. Domino Effects Evaluation problem

In this paper an approach for optimizing the taking of precaution measures to prevent domino effects is proposed. We refer to this optimization problem as the ‘Domino Effects Evaluation (DEE) problem’.

Optimizing the decision process for taking prevention measures in a complex chemical industrial surrounding requires quantifying the danger (with respect to domino effects) of every possible path consisting of domino effects in the area. These data allow for ranking these paths in the network and for taking objective safety management decisions.

Hence, solving the DEE Problem is possible by first developing an approximation algorithm for determining the general longest path in a network and second by developing an algorithm for enumerating all other paths with decreasing length between every pair of nodes in the network. This solution has the advantage, once it is written, of being very complete, but it has the disadvantage of being a combination of very complex problems, the general longest path problem is NP-hard [19], where no satisfactory algorithms do exist until today, as explained in the next section.

3. Literature review

For solving the Domino Effects Evaluation Problem by an approximation algorithm approach, a longest loopless path from s to t in a subgraph of G has to be computed with respect to the Domino Danger Units. This problem can be regarded as an operational research topic, called the general longest path problem. Although it is very similar to the shortest path problem, the algorithms for shortest paths cannot be used to solve this problem. The problem is NP-hard (Garey, 1978) [19], hence no known exact solution exists except for full enumeration. However, the approach of developing an approximation algorithm can be considered when tackling the DEE Problem, although not with approximation results within a constant approximation ratio (Karger, 1997) [20].

In 1995, Alon *et al.* introduced the *color-coding* method [21] for computing loopless paths. This approximation algorithm finds a path of length $\Omega(\log L)$ from a specified

source node to a specified destination node with a performance ratio bounded from below by $(\log n / n)$. To the best of our knowledge, this is the best ratio for a maximum cardinality source-destination loopless path, where by cardinality of a path the number of arcs composing the path is indicated.

Scutellà (2003) [22] developed an improved approximation algorithm, using the color-coding technique in its version specialized to compute loopless paths of a specified cardinality k in a given graph. The color-coding program was extended to approximate the maximum cardinality of the loopless paths, when the source and the destination of the paths are given, and also to address the presence of arc lengths. The extensions are then used to derive approximation results for the general longest path problem. The algorithm guarantees an approximation ratio $\geq (\log n / [n\delta + \log n])$, in $O(nm \log n)$ time, where δ denotes the maximum mean length among all the directed cycles of G . To the best of our knowledge, no other approximation result has been derived for the general longest path computation.

The further ranking of the k longest loopless paths in a directed graph can be viewed as a dual problem of the k shortest loopless path problem, being a well-known optimization problem. The problem was originally examined by Hoffman and Pavley [23], but nearly all early attempts to solve it led to exponential time algorithms [24]. The k shortest path problem arises in a surprisingly large number of optimization contexts. They include situations in which for example model evaluation, sensitivity analysis or generation of alternatives is useful to gain better understanding of the problem. Various papers have been published on the subject, such as [25], [26] and [27]. The most recent developments of finding algorithms for ranking optimal paths in a network are given next.

The best result known to date is an algorithm by Yen [28], generalized by Lawler [29], which using modern data structures can be implemented in $O(kn(mn + n \log n))$ worst-case time. While Yen's asymptotic worst-case bound for enumerating k loopless shortest paths in a directed graph has not been beaten yet, several heuristic improvements to this algorithm have been proposed and implemented, as have other algorithms with the same worst-case bound [30].

Jimenez and Marzal (1999) [31] present the Recursive Enumeration Algorithm (REA). This algorithm is especially well suited for graphs in which shortest paths are

composed by a small fraction of the nodes in the graph. The REA recursively computes every new s - t path by visiting at most the nodes in the previous s - t path, and using a heap of candidate paths associated to each node from which the next path from s to the node is selected. The total time required to find the k shortest paths in order of increasing length after computing the shortest path from s to every node, is $O(m + kn \log(m/n))$.

Martins and Pascoal (2000) [32] offer a deviation algorithm for efficient ranking of optimal loopless paths, as long as an algorithm to compute the optimal path between a given pair of nodes exists. When considering the worst-case for this algorithm, all the n nodes in the network have to be analyzed, and for each one of them an optimal loopless path problem has to be solved. Therefore, assuming that solving such a problem demands $c(n)$ operations, the computational complexity of the proposed ranking algorithm, for the loopless case, is $O(kn c(n))$.

Hershberger *et al.* (2003) [33] describes a new algorithm to enumerate the k shortest loopless paths in a directed graph based on a *replacement paths* algorithm proposed recently by Hershberger and Suri [34]. The algorithm improves the algorithm by Yen yielding a factor $\theta(n)$ speed advantage for the problem in most cases. The Hershberger algorithm is never much worse than Yen's, and on graphs where shortest paths have many edges, the improvement is substantial. However, the (fast) replacement paths subroutine is known to fail for some directed graphs.

Literature research indicates the difficulties for solving the DEE Problem using a combination of an approximation algorithm with a full longest path enumeration approach. Therefore, another computation approach for developing a factor which makes safety measures prioritization more objective is suggested in the next section.

4. An enumeration approach for the Domino Effects Evaluation Problem

4.1. Introduction

Identifying the most important domino effects paths in a chemical industrial area can also be accomplished using the approach of enumerating all possible paths in a graph with n nodes and m arcs. This approach offers exact results, but is limited to small problem instances because of exponential increasing computation time.

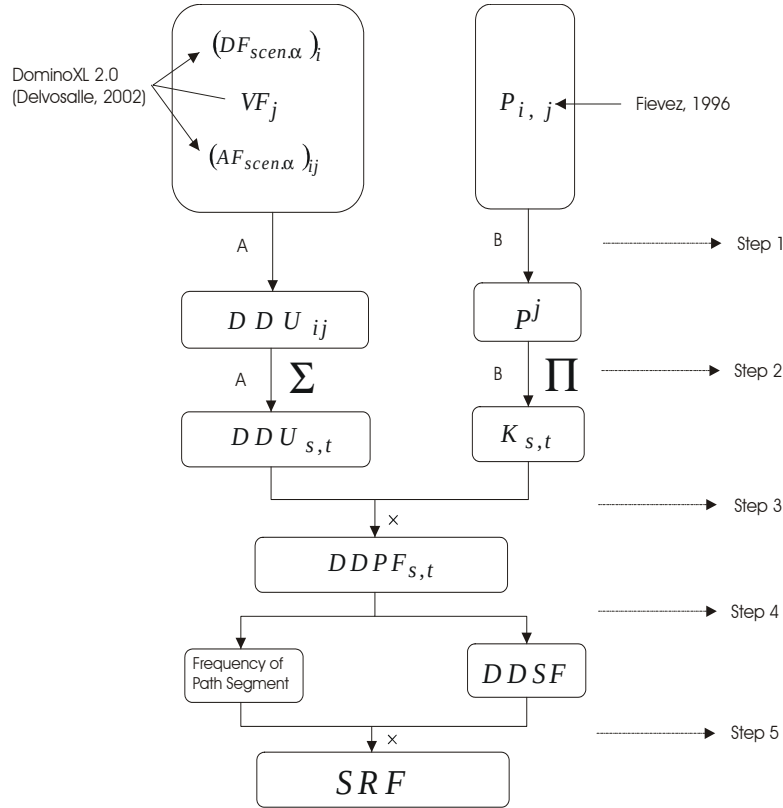
Therefore, the network problem can be tackled by repeatedly enumerating all possible paths in every small subnetwork combination (consisting of for example 5 nodes) resulting in a list of all possible paths consisting of three to four domino effects. Such an approach is justified, because literature research on major accidents where domino effects are involved revealed that it is very difficult and often impossible to discern and to analyze domino effects with cardinality greater than three (Fievez, 1996) [18]. Besides, propagating domino effects should also be stopped as early as possible in a chain in order to keep the consequences of the accident under control.

For these reasons, the constraint is made that not more than four successive domino effects are allowed to happen. Given a directed graph $G = (N, A)$ with $N \geq 5$, all possible combinations of 5-noded subgraphs have to be listed. Our aim is then first to enumerate all feasible paths in order of decreasing length between each pair of nodes in the subgraphs, second to use this information to enumerate and to rank all feasible 3-noded sequences according to the risk they represent for initiating or propagating catastrophic domino accidents. Especially in case of the DEE Problem, the enumeration solution seems to be the best choice, since the original network is reduced to a number of 5-noded graphs.

Sequences (or segments) consisting of three installations where two successive domino effects can occur, represent easy parameters to understand locations in the network where danger towards domino accidents is the greatest. Investigating more installations per sequence (for example by considering 4-noded segments) is more difficult and thus suboptimal for decision-taking, whereas 2-noded segments do not represent domino accidents.

Using the Domino Danger Units matrix and using probability data of domino events (see subsections 2.3 and 2.4), a 5-step method for quantifying the problem is elaborated in Figure 1.2 by calculating a “Segment Risk Factor” (SRF).

Figure 1.2 SRF Computational Hierarchy



The first step consists of using data provided by previous research on domino effects for calculating

- (A) unidirectional units (DDU_{ij}) representing the danger for such effects from a source installation (i) towards a destination installation (j) in a network;
- (B) the probability of a domino effect occurring at every installation (P^j).

In the second stage, an overall danger unit of every network path ($DDU_{s,t}$) and a probability unit of propagating domino paths ($K_{s,t}$) is determined. The third step leads to a path danger factor ($DDPF_{s,t}$) being the multiplication result of the

previously derived factors. In the next step, every path is analyzed by listing per segment of three installations, the frequency on the one hand and the segment domino danger on the other. These data lead to the Segment Risk Factor (*SRF*) by simple multiplication.

Thus in the approach used in this research every possible subgraph combination consisting of five nodes is systematically analyzed. Subsequently, the occurrence probability of every enumerated domino path of each small network is determined. Taking the overall domino danger unit and the overall probability of a path into account, we can calculate an expected Domino Danger Path Factor. A classification can be made using the occurrence frequency of 3-noded path segments as one factor and the sum of the Domino Danger Path Factors of paths including the 3-noded path segments as another factor. Such a ranking is important because safety managers have to make proactive priority choices in the most efficient way where to take safety measures. All possible domino paths between any source node s and a chosen terminal node or so-called sink node t ($s \neq t$) in such a subnetwork, are enumerated. The accumulated Domino Danger Unit per path is calculated. By then examining every feasible 3-noded path sequence out of every enumerated domino path, we can draw conclusions upon domino chain accidents. We acquire a perception of the most dangerous path segments of two adjacent arcs in a complex installations network. The exercise results in a clear objective relative ranking of priority installations where precaution measures need to be taken.

4.2. Relative Ranking

Relative ranking [35] is an analysis strategy that allows comparing the attributes of several items, in casu installation sequences, and provides information on which alternative appears to be the most dangerous sequence. These comparisons are based on numerical values that represent the relative level of danger that is given to each couple of installations. This approach can be applied for example to an existing situation within a chemical cluster of installations to pinpoint the installations where caution is most needed for the prevention of domino effects.

The philosophy behind the relative ranking approach is to determine the relative importance of installation combinations, on-site as well as off-site, from a danger

point of view. Hence, approximate relationships of installation attributes are compared to determine which areas present the greater relative installation hazard or risk.

4.3. Step 1a: The Domino Danger Units Matrix ($DDU_{i,j}$)

A calculation of the *DDU-matrix* by determining every directed Domino Danger Unit (DDU_{ij}) in the installations network is needed. The DDU_{ij} is calculated between every node v_i and the remaining nodes $v_j (v_j \in N; j \neq i)$ in the graph $G(N,A)$.

One contributing Domino Danger Unit factor is the distance between the two installation items. As explained in the introduction, seven possible different major accident scenarios have been defined. The literature [36] provides a distinct theoretical effect-distance, based on every type of scenario and on substance categories. This effect-distance linked to a possible accident scenario from one installation to another can be taken into account in contrast with the real distance between the two installations concerned. Depending on the distance difference, a *distance factor* (AF) can be defined, using three possible categories. If for a specified scenario the real distance between both installation items does not exceed a quarter of the theoretical effect-distance, the distance factor equals 100. On the other hand, if the real distance strictly exceeds the effect-distance, $AF = 0$. In the case that the real distance is strictly bounded by the limits between one quarter and three quarters of the theoretical effect-distance, $AF = 70$. In the final case where the real distance is bounded by the effect-distance and 0.75 times the effect-distance, $AF = 40$.

For evaluating the impact on the different factors in which AF is a contributing parameter and for testing the usefulness of these rather ordinal-based scaling numbers, a sensitivity analysis will be performed.

Calculating a Domino Danger Unit from one installation to another, the potential danger outgoing from all other installations in the industrial complex under investigation has to be taken into account, because every installation might have an impact on the possible progress or continuation of a domino accident.

Hence, another important DDU-factor is the Dangerousness Factor $(DF_{scen,\alpha})_i$ calculated in the domino risk assessment software *DOMINOXL 2.0* (Delvosalle *et al.*,

2002) for a specified scenario α and for an installation v_i in a network of chemical installations. $(DF_{scen.\alpha})_i$ focuses on primary items and scenarios. It allows for classifying pairs of primary equipment zones / scenarios according to the severity of consequences in terms of domino effects. This factor represents the amount of domino danger outgoing from installation v_i to all other installations in the network.

The final contributing DDU-factor is the Vulnerability Factor VF_j (see section 1) focusing on secondary items and scenarios. It allows classifying the secondary equipment zones or pipes according to their vulnerability in terms of domino effects. The Dangerousness Factors for the different scenarios and the Vulnerability Factor have been calculated by the domino software tool *DOMINOXL 2.0*. A matrix of real distances between every installation in the network has also been determined and different effect-distances depending on the scenario are determined using the IDE-document of Baksteen (2003) [36].

Two directed Domino Danger Units can then be calculated for every pair of installations (v_i, v_j) , DDU_{ij} and DDU_{ji} , according to a simple mathematical formula:

$$DDU_{ij} = \left[(DF_{scen.1})_i \cdot (AF_{scen.1})_{ij} + (DF_{scen.2})_i \cdot (AF_{scen.2})_{ij} + \dots + (DF_{scen.k})_i \cdot (AF_{scen.k})_{ij} \right] \cdot VF_j \quad (3)$$

The factor DDU_{ij} is a measure of the danger that installation i represents for installation j in terms of domino effects.

4.4. Step 1b: The installation probability factor (P^j)

Baksteen suggests that domino accident escalation may take place due to three different effects: overpressure, radiation and missile projection. Khan and Abassi (1998) [37] also propose toxic release as a possible cause of domino events. Many methods for the assessment of accident propagation in the literature are based on the identification of threshold values for the primary physical effects. However, the reliability of these thresholds is questionable and different values are suggested by different sources. A solid quantitative assessment requires the estimation of the

probability of propagation (the most promising are propagation functions based on probit functions). However, the few probabilistic models available for propagation probability show relevant differences and sometimes are not consistent. Therefore, a reliable work is still needed in the field (Cozzani *et al.*, 2001).

Since qualitatively ranking domino path segments in a complex network of chemical installations is aimed at, using quantitative data is not obliged. Therefore, instead of using scenario probability data, semi-qualitative installation probability data for the probability assessment of a domino path is made use of.

Historical research of previous domino accidents using the technique of factor analysis has been performed by Fievez (1996) [18] studying 47 domino accidents in which physical effects lead to knock-on phenomena. Factor analysis is a statistical approach that can be used to analyze interrelationships among a large number of variables and to explain these variables in terms of their common underlying dimensions (factors). The objective is to find a way of condensing the information contained in a number of original variables into a smaller set of variates (factors) with a minimum loss of information. For a thorough description of the method, the interested reader is referred to Hair (1998) [38]. The method implemented by Fievez derives, among other things, relative association frequencies between types of primary installations and types of secondary installations.

In a domino effects chain, probabilities of accident events happening due to a successive combination of installations can be regarded as independent occurrences (even if they are not), while this research aims at a relative ranking allowing for the use of ordinal data. It must be stated that an independent occurrence approach can be a clear overestimate of the real domino chain probability.

The probability of a domino accident propagating with node j as a link node of the domino chain, can thus be calculated if P^j is known. Thus, $P_{i,j}$ is needed for every i . The relative association frequencies between two installation types, j being the primary installation and i being the secondary installation, can be used to quantify $P_{i,j}$ using qualitative information.

4.5. Step 2a: The Domino Danger Unit of a path

The accumulated $DDU_{s,t}$ of a path $p = \langle s, a'_1, v'_2, \dots, v'_l, a'_l, t \rangle$ is obtained by summing the individual DDU_{ij} of the 2-noded segments of the path. Thus,

$$DDU_{s,t} = \sum_{\forall ij=i(i+1) \in \text{seg}_{xy}^{p_{s,t}}} DDU_{ij} \quad (4)$$

4.6. Step 2b: The probability of propagating domino paths ($K_{s,t}$)

The probability of a feasible domino path occurring in an installations network can be calculated as follows:

$$K_{s,t} = P^s \cdot P^{v'_2} \cdot \dots \cdot P^{v'_l} \cdot P^t \quad (5)$$

4.7. Step 3: The Domino Danger Path Factor ($DDPF_{s,t}$)

The $DDPF_{s,t}$ is determined by multiplying the overall Domino Danger Unit of the path and the overall probability of the path:

$$DDPF_{s,t} = DDU_{s,t} \cdot K_{s,t} \quad (6)$$

For every possible domino path p in the chemical industrial area, a Domino Danger Path Factor ($DDPF$) is calculated.

4.8. Step 4: The Domino Danger Segment Factor (DDSF) and the path segment frequency

The segment frequency is obtained by counting all the paths where the 3-noded segment is being part of in the entire installations network, whereas the overall $DDSF$ is obtained by summing all $DDPFs$ of the paths where the segment is being part of in the network.

4.9. Step 5: The Segment Risk Factor (SRF)

The *Segment Risk Factor* is calculated by multiplying the frequency of the path segment with the overall *DDPF* of the path segment or the Domino Danger Segment Factor (*DDSF*).

5. Summary and conclusions

For preventing domino accidents, first of all reliable risk assessment studies have to be carried out. In spite of the destructive capability of such accidents, and the potential domino risks which many industries face worldwide, assessing these phenomena has received much less attention than other aspects of risk assessment. Because of the complex nature of domino effects, it is very difficult to assess such events. In the last decade, a variety of computer automated tools have been developed for determining the possibility of domino effects. However, these tools do not offer transparent answers for prioritization of the taking of domino prevention measures in a complex surrounding of chemical installations. Nevertheless, managerial decisions on preventing such catastrophic major accidents have to be made as efficiently as possible, safety-related as well as towards economical constraints.

In this paper, a methodology for the relative ranking of sequences of chemical installations towards their danger for producing escalating domino effects is proposed. Such a tool will be used as part of a decision support system to prevent domino accidents.

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