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Resilience of chemical industrial areas through attenuation-based security

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ABSTRACT

This paper investigates the possibility of attenuation-based security within chemical industrial areas. Representing chemical industrial areas as mathematical networks, we prove by case-study that the resilience to disaster of such areas may follow a power-law distribution. Furthermore, we examine what happens to the network when highly hazardous installations would be intelligently protected against malicious acts: the network disintegrates into separate smaller networks. Hence, islands are formed with no escalation danger in between. We conclude that it is possible to protect chemical industrial areas in such a way that they are more resilient against terrorism.

1. Introduction

The importance of the chemical industry in the global economy can hardly be underestimated. From food packaging to pharmaceuticals, the chemical industry indeed has a prominent role in creating and maintaining our modern day lives. For various reasons, such as benefits of scale, exchange of material streams, optimization of energy streams, and the like, there is a long tradition of strong cluster-like linkages in the chemical industry. Chemical industrial clusters can be found around the world, and they are expanding ever more. According to De Langen [8], an 'industrial cluster' can be defined as a "geographically limited concentration of mutually related business units, associations and public or private organizations centered on a specific economic focus". If looking at a chemical industrial cluster, we may define it as a 'geographically limited concentration of manufacturing companies and service providers operating in the chemical business'. Chemical clusters may consist of tens of different chemical plants and chemical Logistic Service Providers situated in each other's vicinity, to sometimes hundreds of organizations. As such, these chemical industrial parks consist of hundreds to thousands of different chemical installations such as storage tanks, process equipment, chemical reactors, etc. Large chemical clusters worldwide include those of Houston (USA), Antwerp (Belgium), Rotterdam (The Netherlands), Tarragona (Spain), the Rhein-Ruhr region (Germany), Durban (South Africa), Edmonton (Canada), Shanghai Chemical Industry Park (China), and many others.

The security of these chemical industrial parks is important for regions and the countries where these clusters are situated and operate, as well as, in some cases, for the global economy.

Many chemical industrial parks have already been built at some location. Hence, environmental design-based security of these clusters is not possible anymore. However, looking at the five different principles of design-based safety (principles that can also be used for the purpose of design-based security), the fourth principle, attenuation by limitation of effects, or in other words by decreasing the possible extent of the undesired outcome (comparable with 'compartmentalization' in case of fire safety), can be used in existing industrial parks. Fig. 1 provides the five principles of design-based safety (based on [11] and [12]).

Attenuation of the consequences of a large-scale accident within a chemical cluster can indeed be important for the survival of a cluster as a whole. Security based on the 'attenuation of consequences' principle can therefore be seen as a way to make a chemical industrial area more 'secure by design'.

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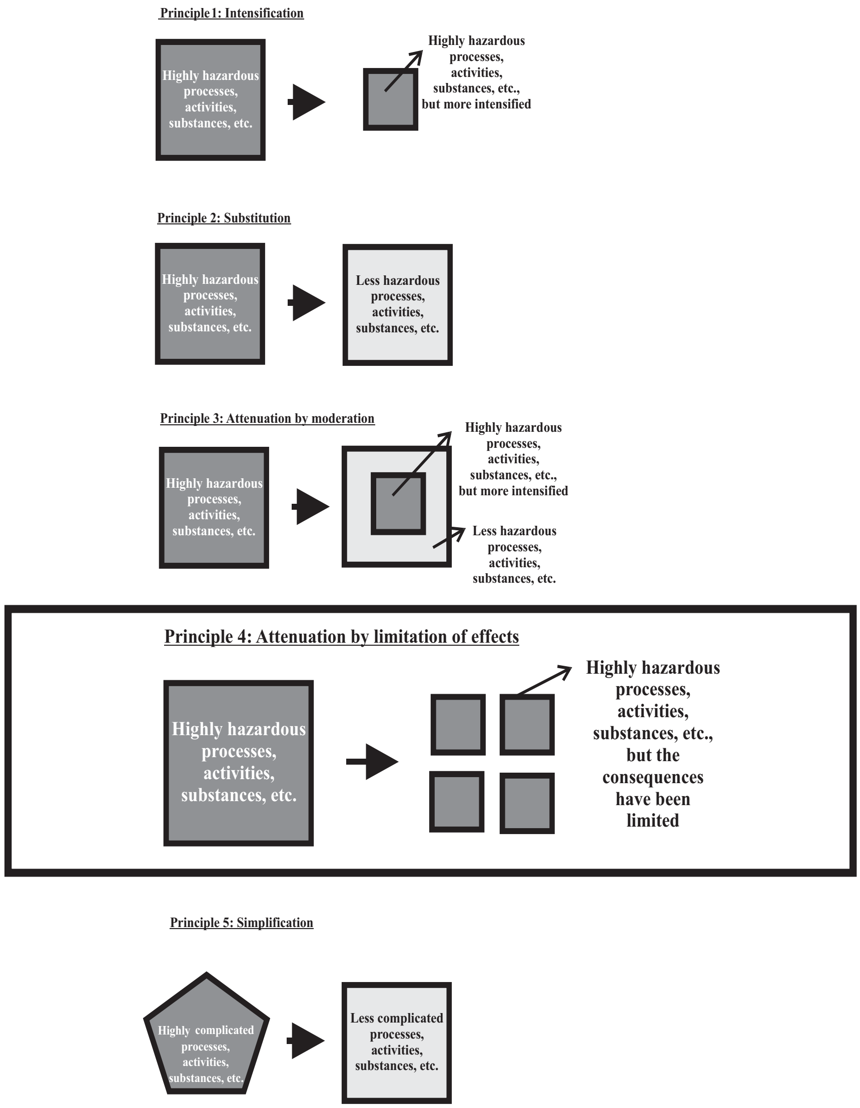

Fig. 1. Five principles of design-based safety.
Source: based on [12].

Another way to look at the attenuation principle, is that it builds resiliency into the chemical cluster. Resilience as a concept, can be looked upon from different angles. Often, resilience is understood as some kind of capacity or ability to recover relatively quickly after an important undesired event (see e.g. [3]). Obviously, such understanding of resilience only takes the re-active part of the concept into consideration, while resilience concerns both the re-active and the pro-active part of dealing with major mishaps. Therefore, in this article, we use the definition by Leveson et al. [14] stating that resilience is "the ability of systems to prevent or adapt to changing conditions in order to maintain (control over) a system property". The property we are concerned about in this article is security (of a chemical industrial area). As Leveson et al. [14] put it, the system must be resilient in terms of avoiding failures (deliberately induced or not) and losses, as well as responding appropriately after the fact.

As indicated by Kröger [13], single failures may develop into serious breakdowns and cascade into dependent systems. To reduce vulnerabilities, risk governance strategies should be developed including all major actors in the decision-making process. Improved analytical capabilities to overcome deficits of 'traditional' methods in coping with complexity, should be developed. Chemical industrial areas form no exception to this observation. In this context, the concepts of self-organized criticality (SOC) and highly organized tolerance (HOT) are interesting study drivers linking real-world phenomena with power-law scaling. However, as Markovic and Gros [15] indicate, current experimental evidence is still inconclusive with respect to a possible causal relation of the emergent power laws to an underlying self-critical state. These authors also indicate that it is possible in many circumstances to tune a system toward a critical point. When considering a chemical industrial area to be 'the system', it would thus be interesting to verify whether it follows a power-law.

Chemical industrial areas can be seen as critical infrastructure subject to a cascade effect: if one installation is blown up, other installations in this area may be affected. There may evidently be an influence of the built-in safety of certain chemical installations on the likelihood of success of a malicious act on such installations, and safety may thus be a parameter to be considered while investigating resilience. However, this is only the case in some instances and it cannot be generalized. In case of a chemical industrial area, it is thus interesting to verify how resilience to protect against terrorist attacks, can be achieved. A chemical park cannot be easily compared with another socio-technical system, such as for example a single chemical plant. Chemical industrial parks are characterized by different organizational cultures (and hence, different security cultures and various security climates), different top-management security visions and missions, different security strategies, etc. Therefore, making an entire chemical industrial cluster resilient against threats by means of attenuating the possible consequences of a malicious act, is different from making a single company more resilient. Indeed, a single organization can for example be made more resilient by using the High Reliability Organization principles described by Weick and Sutcliffe [27] or by using certain technology. However, the implementation of these principles or of technology is focused on single organizations with one organizational culture and one top-management having the ability to impose solutions. The effectiveness of implementing the High Reliability Organization principles and of implementing technological solutions in industrial practice actually depend on an organization's top-management commitment and engagement. It would be very difficult, if not impossible, to apply them within a cluster of organizations characterized with a variety of top-managements with different opinions and (sometimes hidden) agendas.

Before investigating how an entire chemical industrial cluster, looked upon as a system, can be made secure from a attenuation-based viewpoint, the question should be answered whether there is in fact, as assumed, a need for protecting such industrial areas against terrorist attacks, or not. This will be investigated in the next section.

2. Terrorism and the chemical industry

A Threat Assessment (TA) takes all the threats from inside and outside an organization into account. A TA is a specific step in a security risk assessment, and can be briefly explained as a method to determine the threat capabilities, strength, motives, weapons, tactics, and likelihood of attack [23]. As indicated in API Recommended Practice 780 [1], a Threat Assessment is an important part of a (company) security management system. There is a need to identify and understand the threats facing the industry and any given facility, installation or location in order to properly respond to those threats. A Threat Assessment is usually part of the security management process of a single company and helps to establish and prioritize security-program requirements, planning and resource allocations. The determination of the threats posed by different adversaries leads to the recognition of vulnerabilities and to the evaluation of countermeasures required to manage the threats. Srivastava and Gupta [26] for example developed a methodology for security risk assessment in the oil and gas industry.

Threats also exist against chemical clusters and not merely against individual chemical plants. Besides all other advantages and responsibilities going hand in hand with the settlement of chemical plants in industrial parks, such companies are indeed linked through the responsibility of dealing with security needs in the industrial cluster. Security does not stop at an organization's fences, since a terrorist action can deliberately induce an accident within a company with cross-plant consequences, and may cause even more severe accidents in nearby companies, compared with the company where the attack originated from. This understanding needs to be viewed in terms of the prevention with respect to escalating accidents (or domino effects) between plants.

Salzano et al. [25] studied the potential of escalation effects in a chemical industrial area related to home-made explosives (AN/dolomite (50/50)+diesel fuel). The authors report that a terrorist attack with limited quantities of explosive (100 kg) detonated close to storage tanks, may actually lead to domino effect escalation. The authors also studied a more severe terrorist attack using 50,000 kg of home-made explosives loaded on two trucks located at about 130 m from the storage tank area, and report that due to the high stand-off distance, the escalation was very limited. Salzano and his colleagues however did not consider a scenario with large amounts of explosive located close to the chemical storage. The latter scenario would for example be the case if several trucks filled with large amounts of explosives could be driven on purpose into certain pre-determined installations, such as is the case in an intelligent large-scale induced domino-effect scenario. Although this doom scenario was not investigated by Salzano et al., it is clear from the study that such could possible lead to large devastation.

The commission staff working document on the review of the European programme for critical infrastructure protection [9] indicates that there are methods following a linear approach, consisting of the identification and classification of threats, the identification of vulnerabilities, and the evaluation of impact. Such an approach to tackle security risks, although well-known and widely used amongst security experts, fails to capture systemic risks and is therefore rather myopic in its possible use. Countermeasures against terrorist threats based on current Vulnerability Assessments are thus limited to immediate consequences and are neither designed to prevent an accident attaining systemic proportions, nor to effectively limit the consequences of a large-scale terrorist attack in a chemical cluster consisting of more than one plant. State-of-the-art security assessment therefore e.g. prioritizes chemical installations with respect to their vulnerability for domino effects in an industrial area, irrespective of the size and composition of the area [21].

Tackling security risks within a chemical cluster requires the cluster to be modeled as a networked system, since the risks will have a systemic character [20]. To mathematically investigate the dangerousness and the vulnerability properties of an entire industrial area composed of a diversity of chemical plants, requires the area to be modeled as a network of chemical installations. The efficiency and effectiveness of the protection of an industrial cluster, seen as a network, can then be intelligently worked out. The question thus is how a chemical industrial area can be modeled in a practical way that can be used to attenuate the consequences of terrorist attacks and prevent them from becoming a large-scale terrorism disaster. Safety- and security-related protection synergies such as those resulting from the application of inherent safety principles, are highly beneficial, and should be fully considered when designing protection within an industrial area. Several important advantages of consequence-attenuation in case of deliberate disaster can be listed:

(i) There is no need for new security legislation (driven by public perception after a terrorism disaster in a Western chemical cluster);
(ii) The number of casualties and the amount of economic losses can be limited;
(iii) A point has been made to the adversary that chemical clusters are intelligently protected;
(iv) It prevents large industrial losses, possibly having an important impact on local economy and even, in certain cases, on global economy;
(v) Citizens are demonstrated that their economic interests are preserved, and that the chemical industry deserves its license to operate.

So attenuation-based security and resilience of chemical industrial areas is very important indeed, leading to a win-win-win situation advantageous for society, individual citizens, as well as for the chemical industry. One question still remains: would it be satisfactory to deal with attenuation-based security on an individual chemical plant level, or should the problem be looked at from a cluster point of view? This question is investigated in the next section.

3. Plant security versus cluster security in the chemical industry

3.1. Size of the chemical industrial area

As already indicated in the introductory section, a single plant and a cluster of adjacent plants contain many dissimilarities in terms of management, including security management. To manage security in a cluster of chemical plants, there is need for collaboration on strategic, tactic, and operational levels. Especially systemic risks, where one accident may lead to one or more secondary accidents and so on, may need to be treated differently depending on the size of the industrial area, that is, depending on the number of chemical installations that is considered simultaneously. Obviously, an amalgam of chemical companies will not be made resilient easily from a managerial point-of-view. From a technological perspective however, it should be possible to intelligently apply the ‘attenuation of consequences’ principle, and hence, to make an industrial area more resilient against terrorist attacks.

Before intelligent protection of a chemical cluster can take place, we have to find out the impact of the number of installations on the level of systemic risk of a chemical industrial area. By doing so, we can investigate whether chemical clusters are in fact vulnerable due to their size. An approach to study the possible consequence of the number of nodes in a network, is to verify whether the network is subject to a power-law. Many natural and man-made phenomena follow statistical rank-size laws, called power-law distributions, that relate the size of the phenomenon to the frequency of its occurrence. Actually, power-law distributions can be regarded as a mathematical–statistical-version of the well-known 80/20 rule, the intuitive notion that 20% (or in general, a small fraction) of events cause 80% (or in general, the large majority) of the impact [2]. Phenomena in biology, economics, geography, sociology, etc. follow such a power-law distribution.

3.2. Investigating power-law distributions in chemical clusters

Cohen et al. [5] as well as Callaway et al. [4] indicate that random networks fall apart after a critical number of nodes have been randomly removed. However, they found that for power-law distributed networks the critical threshold disappears in cases where the degree exponent is smaller or equal to three. Therefore, such networks break apart only after all nodes have been removed. However, this feature also has a down side: the removal of a few selected nodes (displaying high connectedness) may break the network down into isolated pieces. One can thus also put it this way: in a network following a power-law distribution, if a small fraction of especially selected nodes is removed, it breaks apart. Hence, in terms of a chemical industrial area, if it would follow such a power-law, a small fraction of chemical installations being protected against terrorist acts will have a profound security-enhanced impact on the chemical cluster as a whole. The cluster could thus be topologically strong with respect to selected protection. Power-law distributed chemical clusters thus harbor a possibility to attenuation-based security.

In a situation where there is no protection against attacks, such power-law distributed networks combine a robustness of random failures with a vulnerability to attacks. The price of the topological robustness of power-law distributed networks is thus their exposure to intelligent attacks. In the case of a chemical industrial park, this would obviously be terrorism. Causing a hierarchy of highly dangerous chemical installations to explode or to set on fire, may bring the entire chemical cluster down. Since the attacks of 9/11 in 2001, the Madrid bomb attack on a passenger train in 2004, the subway attacks in London in 2005, and other terrorist attacks and threats ever since, there has been an increased awareness toward issues of vulnerability of chemical industrial activities against terrorism. It is therefore crucial to learn at what scale the chemical installations forming a chemical industrial area display power-law characteristics – at the scale of 50 installations, or 200, or even more, or maybe never.

To this end, we investigate the power-law distribution of different sizes of chemical installations' networks. The global Lambert coordinates allow positioning the installations in relation to each other. Real distances are calculated by using the Lambert position coordinates of the installations. Theoretical domino effect distances are related to possible physical effects that may cause the propagation and escalation of a primary undesired event (accident scenario) in the other installations of a network. Reniers and Dullaert [17,18] used the so-called Instrument Domino Effects (abbreviated IDE) [24] to determine accident scenarios and theoretical domino effect distances. Accident scenarios included in the IDE are: the bursting of pressure vessels, BLEVEs giving rise to fragment projection, VCEs, pool fires, and jet fires. The definitions of these accident scenarios are based on the definitions given in the Purple Book [7]. To define a domino distance, the IDE only considers containment systems and installations with explosive, flammable, highly flammable or very highly flammable substances. The IDE offers tabulations of calculated domino distances for standard couples of installations, and with no obstacles of any kind between the installations (and hence, the distances are conservative and are a rough simulation of real circumstances). The figures obtained are based on various parameters such as scenarios considered, quantities of hazardous substances, substance categories, generic substances, and protection- and vulnerability levels of the exposed installations. For cases deviating from the standard procedure (e.g. mixtures of substances), a method described in the IDE can be used to manually calculate the theoretical domino distances.

Although the IDE was employed to determine the theoretical domino effect distances, it should be clear that other, alternative, methods with respect to IDE may as well be used to the same aim. The methodology proposed has a general validity and is not necessarily linked to the IDE method for preliminary escalation assessment. More information on methods to determine theoretical scenario distances for domino effects, can e.g. be found in Cozzani et al. [6] and Reniers and Cozzani [22]. Kadri et al. [10] for example worked out a method for quantitative assessment of domino effects in industrial areas, thereby considering failure probabilities.

As mentioned previously, resilience of a single chemical plant may not necessarily be identical to resilience of a chemical industrial park. To investigate the dependence of the distribution on the scale of the industrial area, it needs to be seen and mathematically translated into a networked system. A chemical industrial area consists of a number of separate chemical installations, which can be mutually linked in terms of the level of danger they pose to each other. We thus consider installations, irrespective of their location in an industrial area, to be the nodes of a network and we let the amount of danger between the installations be represented by the edges linking the nodes together. Using this approach, we model a chemical industrial area as a connected weighted network.

To do this, we use the method as elaborated by Reniers and Dullaert [17,18]. The method calculates the weight of each link between two chemical installations in either direction (using the IDE), and expresses this weight as a simple scalar. The amount of danger for initiating or continuing escalating accidents is represented by this scalar. Reniers and Dullaert [17,18] and Reniers [19] refer to this number as the ‘Domino Danger Unit’ (DDU). By calculating all unidirectional Domino Danger Units between all chemical installations forming a network, an installations danger matrix DDU of order $N \times N$ (with N the number of installations in the network) is obtained. For more information on this approach, we refer to Reniers and Dullaert [17,18] and Reniers [19].

A Domino Danger Unit can thus be employed to express the escalation dangerousness from one installation to another. Furthermore, the "out-strength" S_i^{out} of a node i can be introduced:

$$S_i^{out} = \sum_{j(\neq i) \in G} \mathrm{DDU}_{ij}$$

The installation out-strength is thus obtained by summing all DDUs outgoing from one installation to all other installations in the industrial area. Such summation delivers us an approach to estimate the relative 'hazardousness' – or in other words the 'danger level' – of an installation within a network of installations with respect to escalation effects.

3.3. Case study

Let us now take the example of a real industrial area to verify whether a chemical industrial area may display power-law characteristics. The Antwerp chemical industrial cluster is the second largest area worldwide where chemical companies are concentrated. The data needed for calculating the DDUs was collected by using information available within publicly available safety reports of the companies concerned. Within the Antwerp petrochemical cluster, an industrial area composed of two international companies (both oil majors) was selected. All installations belonging to the industrial area were considered as input for determining the DDU-matrix and ultimately the power-law distribution.

The industrial area is characterized by a surface area of 168 ha, a number of FTE employees working in the area of approximately 1400, and a total number of 287 chemical installations to be investigated. One company was represented by 227 installations, and the second company owned 60 installations. Chemical installations can be atmospheric or pressurized storage tanks, process equipment, cryogenic storage, loading and unloading areas.

For these industrial areas composed of 60, 227, and 287 installations, we calculate the networks linking the installations together with dangerousness links, having weighting factors (DDUs). The networks, represented as matrices of DDU figures, are further used to calculate the power-laws of the represented industrial areas, and to verify whether such chemical industrial areas may indeed follow a power-law. Furthermore, we are interested, if there would be power-law distributions, what is the impact of the size of the area, and what is the consequence of intelligently protecting installations.

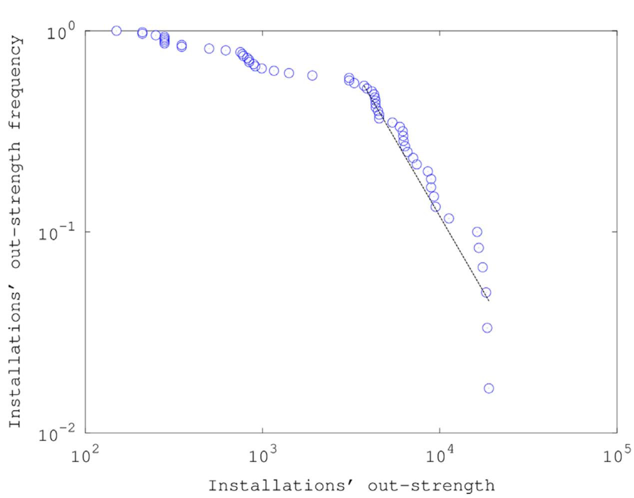

Fig. 2. Power-law plot of the company 1 industrial area (60 installations) against empirical data.

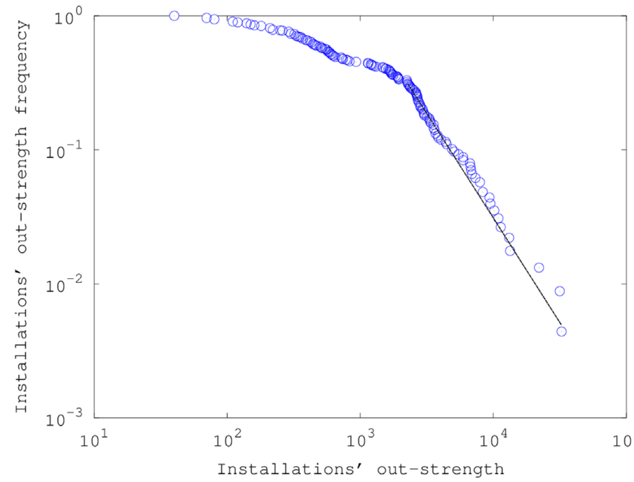

Fig. 3. Power-law plot of the company 2 industrial area (227 installations) against empirical data.

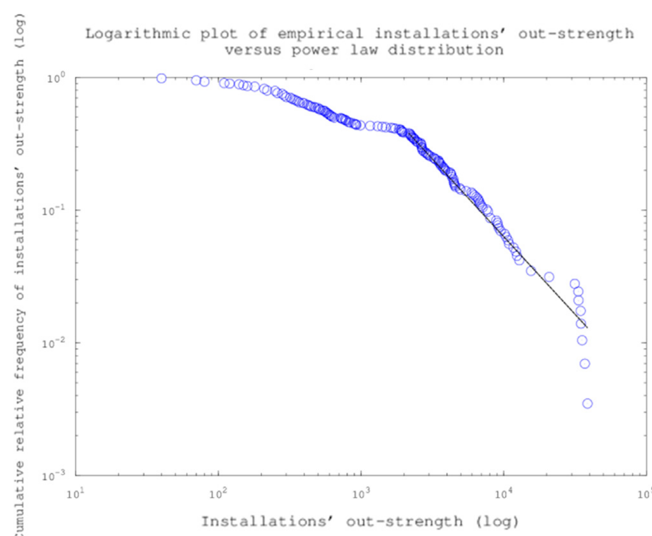

Fig. 4. Power-law plot of the entire industrial area (287 installations) against empirical data.

3.4. Power-law distribution study using the case study

To be able to understand the importance of the high-danger installations within the studied industrial area, the power-law distribution was investigated for the network of both companies (60 and 227 installations), as well as for the entire industrial area of 287 installations. We display in Figs. 2–4 the power-law distributions plotted against empirical data. A data point in this figure is a pair of values (x,y) with x being a value of out-strength, and y being the relative number of installations that have an out-strength at most equal to x (i.e., the number of installations with an out-strength less than or equal to x divided by the total number of installations).

Figs. 2–4 show that some (high-danger) installations may indeed act as "very connected" installations for initiating or continuing domino effects, and that actually the three areas very likely follow power-law distributions. To verify this, we calculated the corresponding power-law distributions of the three plots, and they are given by

(i) Company with 60 installations: $p(x) = 409,751x^{-2.52}$.

(ii) Company with 227 installations: $p(x) = 271,844x^{-2.56}$.
(iii) Cluster of two companies with 287 installations: $p(x) = 9319x^{-2.17}$.

with x=the installations' out-strength (log). Remember that the out-strength can be regarded as the installations' hazardousness for initiating and/or continuing knock-on effects.

Hence, the network of DDUs representing the three studied industrial areas of 60, 227, and 287 chemical installations respectively, indeed follow a power-law and the exponents equal 2.52, 2.56 and 2.17, respectively. This power-law exponent, also called "alpha", provides us with an idea of the impact of a large-scale domino effect caused or continued by high-danger installations.

As already mentioned in the previous section, the conclusion that the areas follow a power-law distribution may dramatically influence the way the chemical industrial area networks break down, and hence, how they can be intelligently protected (or not) and thus not break down. Random failures of – or attacks on – high-danger installations will not have a major impact on the networks, but intelligently designed failures or attacks may have a profound (and possibly devastating) impact on the industrial areas.

From this study, it can be seen that it is possible that the domino danger unit network of an individual plant (with fewer installations than an industrial area consisting of hundreds of installations) follows a power-law distribution. Hence, an individual plant may want to consider determining its power-law situation and eventually take security measures to take attenuation-based security protection measures. However, taking security measures within a group of chemical plants is more optimal due to several reasons. For one, even if an individual plant has taken protection measures in a way that it is more resilient against terrorist attacks, it may still be hit catastrophically by an intelligent attack aimed at one or more nearby companies within the cluster. Moreover, a chemical plant within a chemical cluster should not be treated as 'an island' with respect to escalation danger. This leads to sub-optimal use of means and investments and to sub-optimal protection. Collaboration between the different plants constituting the area leads to an overall view of the industrial area network and its vulnerabilities, and finally to optimal protection of the area.

Making a small-size chemical industrial area more resilient against large-scale terrorism is thus a possible approach, but it is possibly not the optimal solution. Making a large-size chemical industrial cluster more resilient seems to be the best approach, and can be realized by determining the power-law distribution of the area in a first stage, and engineering attenuation-based security in a second stage. How attenuation-based security may be realized, is explained in the next section.

4. Engineering attenuation-based security in a chemical industrial area

We further tested what the impact of intelligently eliminating high-danger (high out-strength) installations of the network was

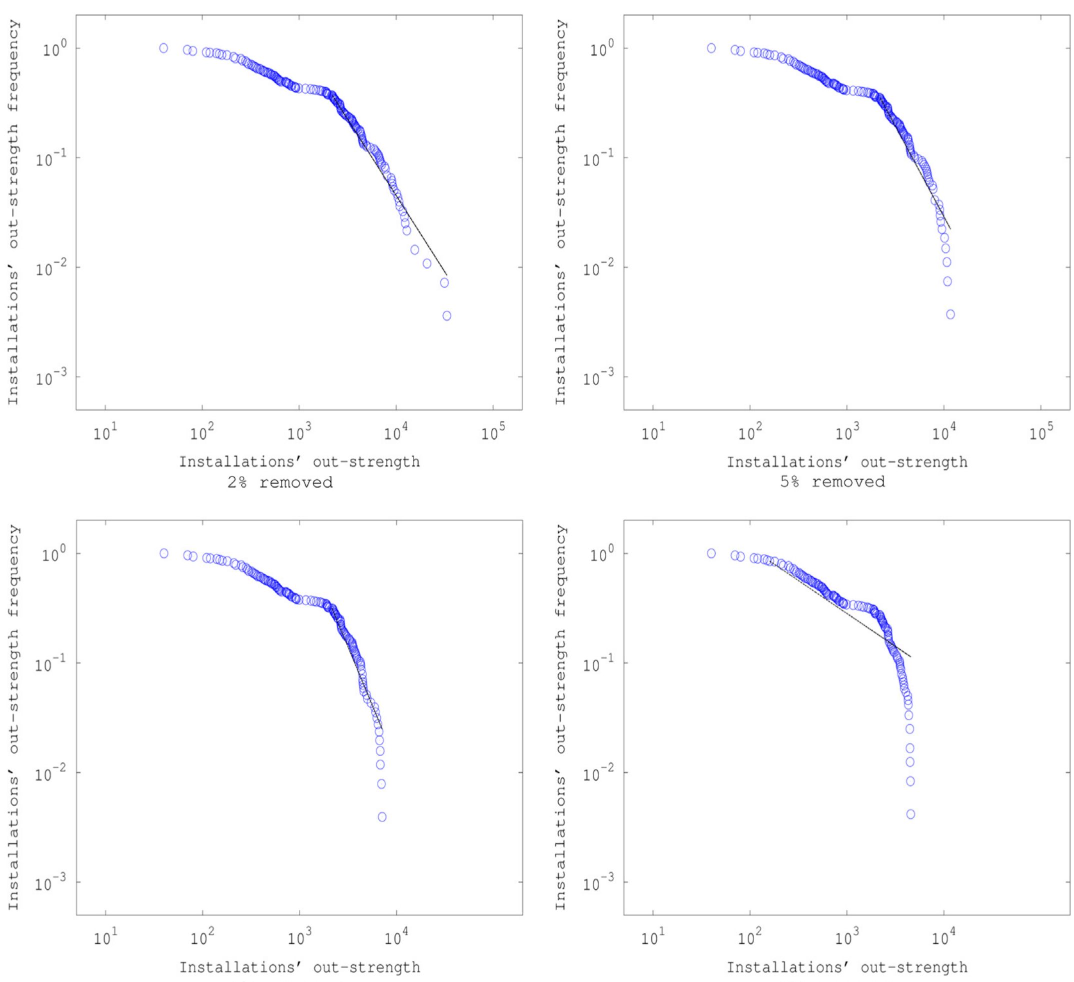

Fig. 5. Power-law plot against empirical data, whereby 2% (upper left panel), 5% (upper right panel), 10% (lower left panel) and 15% (lower right panel) of the highest-danger installations were removed from the cluster network.

on the power-law distribution. We noticed that removing the installations with the highest out-strength resulted in a lower adherence to the power law. This is visually observable in Fig. 5, in which 2%, 5%, 10%, and 15%, respectively, of the most high-danger installations have been removed from the cluster network of 287 installations.

Fig. 5 illustrates that the power-law distribution is actually getting worse when deleting high-danger installations from the network, and even disappears when deleting 15% of the highest-danger installations. The alphas were also calculated for these different situations, and provide confirmation to the conclusions drawn based on the figures. The power-law exponents for the different distributions are: 2.35 (−2%), 2.65 (−5%), 3.13 (−10%), and 1.60 (−15%). Hence, since the exponent must be strictly larger than 2 for the distribution to be defined, the distribution of "−15%" does not follow a power-law anymore (the calculations are not reliable anymore).

Reniers [16] indicates that in an industrial area where the most dangerous installations are removed, 'domino islands' emerge. Hence, in such a case, separate collections of installations with no domino danger connections between each other (Reniers calls them 'domino islands') appear, and the industrial area (as a whole) cannot be destroyed anymore in one strike.

As a result, in a large industrial area where the high-danger installations are removed, or in other words where these high-danger installations would be identified and subsequently well-protected against deliberate acts, the large area disintegrates into smaller areas. These smaller areas will still follow a power-law distribution themselves, but the escalation danger power-law characteristics of the industrial park disappear and the large area cannot be destroyed at once anymore. This way, intelligent protection within a large chemical industrial park will lead to attenuation-based security, and the end-result is a less vulnerable (or more resilient) cluster.

5. Discussion

We studied the resilience of a chemical industrial area via investigating the power-law of the mathematical network representing the area. Following a power-law distribution means that a very large number of installations exhibit low dangerousness, while only a very limited number of installations exhibit very high dangerousness. This implies that such an area is vulnerable to intelligently designed attacks aimed at the high-danger installations in the area, possibly even leading to the destruction of the entire area.

Using information from a real-case chemical industrial area, it only takes a small number of domino effect hops to get from one installation to any other in a chemical industrial area. An area composed of 60, 227, or 287 installations indeed shows power-law behavior. Investigation is thus needed within chemical industrial parks to decide whether or not they have to be regarded as being subject to a power-law. To obtain deeper insights into the industrial area conditions determining the power-law behavior, factors such as the number of installations involved, the distances between the installations, the level and quality of protection taken on the installations, and the size of the area need to be further investigated.

If the high-danger installations of a power-law distributed chemical industrial area are sagaciously protected, the possibility of one terrorist attack destroying the area as a whole, is eliminated. This way, attenuation-based security can be designed into any chemical cluster. The level to which the consequences of a terrorist attack are attenuated, depends on the quantity and quality of protection measures. This is illustrated in Fig. 6.

Until now, chemical enterprises still perform security risk management tasks and execute protection against malicious acts on an individual basis, regardless of nearby plants. To decrease the

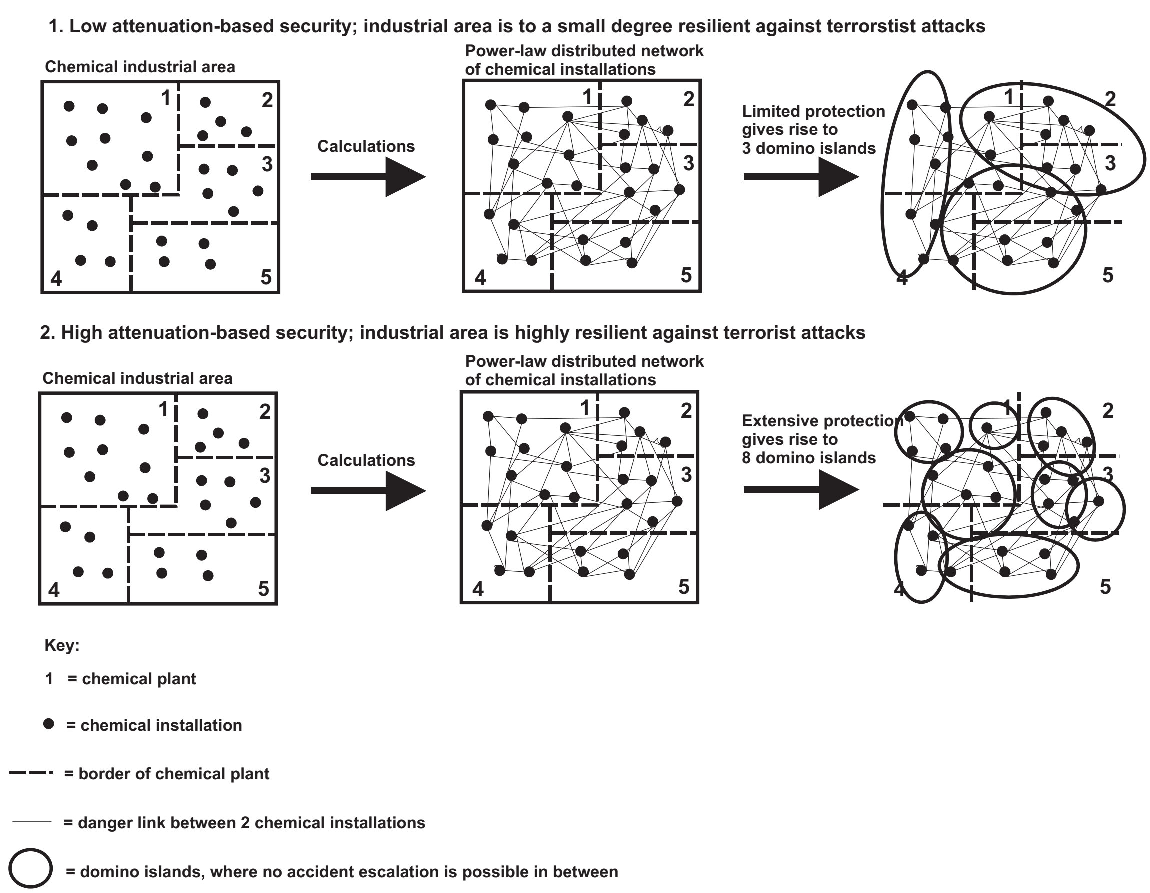

Fig. 6. Attenuation-based security of a chemical industrial park.

consequences of terrorist attacks in an industrial area, it would seem to be much more efficient to consider the area as a whole. For although the odds of a large-scale terrorist attack scenario destroying an entire chemical cluster at once, or a large part of it, are extremely low, they might increase as the industrial area's number of installations and the amount of hazardous materials used, increases. By protecting a small percentage of the high-danger installations of the cluster, the area is divided into smaller sub-clusters without domino danger in between. By first dividing the entire area into smaller areas with no domino effects danger in between, the power-law behavior of the large industrial area is eliminated. Since the different sub-clusters cannot 'affect' each other with escalating effects, they can all be regarded isolated 'domino effect islands'. The latter approach follows the attenuation principle of design-based security.

6. Conclusions and recommendations

In the case of terrorist attacks, it is very difficult to determine the probability or the likelihood of an attack on a chemical industrial park, simply because there is insufficient information available to make such an estimate. Therefore, intelligent protection within a network of chemical installations (drafted based on the possible consequences of accident scenarios, and not considering the probabilities of terrorist acts), seems to be the most justifiable option for further designing intelligent attenuation-based security of the industrial area.

Since we proved in this article by case-study that a chemical industrial area might follow a power-law distribution, very few installations can exhibit very high escalation danger connectivity while others (the vast majority of installations) may have only relatively unimportant dangerousness links. By protecting those high-danger installations efficiently and effectively against terrorism, the possible consequences of an attack can be limited; the large area disintegrates into smaller areas of possible escalation. Hence, an industrial area may be less vulnerable (or more resilient) against the propagation of domino effects within the area. Security considerations thus strengthen the argument for adequate security measures against possible escalation (even if a chemical installation is considered to be safe, it may not be secure) and for separation of units and plants and resilience in their interdependency.

Some interesting areas of future research can be formulated based on the results in this paper. First, it would be meaningful to study the governance of security arrangements in an industrial cluster (e.g., how to share the costs and decision-making, since this would require pooling of resources if security is not to be dealt with on an individual plant basis). Second, the policy and regulatory dimensions linked with the findings might be worth exploring (e.g., on the role for government, federal or local, in providing collective security to industrial clusters). Third, an interesting domain of research also concerns technical issues that provide 'compartmentalization' and uncoupling in case of installation protection in an industrial chemical cluster. Fourth, security issues are best treated, form an academic perspective, within the framework of game theory. A worthwhile future research topic may therefore involve the implications and decisions by intelligent adversaries if it is known and published that specific nodes are deemed more dangerous and better protected than others.

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