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# A multi-attribute Systemic Risk Index for comparing and prioritizing chemical industrial areas

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ABSTRACT

Measures taken to decrease interdependent risks within chemical industrial areas should be based on quantitative data from a holistic (cluster-based) point of view. Therefore, this paper examines the typology of networks representing industrial areas to formulate recommendations to more effectively protect a chemical cluster against existing systemic risks. Chemical industrial areas are modeled as two distinct complex networks and are prioritized by computing two sub-indices with respect to existing systemic safety and security risks (using Domino Danger Units) and supply chain risks (using units from an ordinal expert scale). Subsequently, a Systemic Risk Index for the industrial area is determined employing the Borda algorithm, whereby the systemic risk index considers both a safety and security network risk index and a supply chain network risk index. The developed method allows decreasing systemic risks within chemical industrial areas from a holistic (inter-organizational and/or inter-cluster) perspective. An illustrative example is given.



## 1. Introduction

The concept of ‘systemic risk’ is well known in the financial world where it is connoted with risks, which are common to an entire financial market and not to any individual entity thereof. Systemic risks also exist within the chemical industry. Although the nature of systemic risks (w.r.t. causes, prevention, etc.) is very different in the financial and the chemical sector, the potential consequences are in both cases devastating, both from a social as well as an economic point of view.

In the (petro)chemical industry, economies of scope, environmental factors, social motives and legal requirements often force companies to ‘cluster’. Therefore, chemical plants are most often physically located in groups and are rarely located separately. These clusters of chemical plants consist of atmospheric, cryogenic and pressurized storage tanks, large numbers of production installation equipment, and numerous pipelines for the transportation of chemicals and petrochemicals.

Clearly, such chemical industrial areas are characterized by reciprocal danger between equipment and infrastructures being part of the areas. As such, within chemical clusters intangible interdependencies between equipment and infrastructures may exist from a safety and security point of view. Every chemical installation represents a hazard depending on the amount of substances present, the physical and toxic properties of the substances and the specific process conditions. Hence, such installations present – to a greater or lesser extent – a danger to their environment (and thus to the other installations in the neighborhood). Besides losses of lives, both short and long term disruptions from accidents in the chemical industry have led to significant economic losses and environmental damage [1]. One type of accident particularly interesting in this regard is an escalating accident or a so-called domino effect, whereby one accident at one installation triggers another accident either at the same installation (temporal domino effect) or at another installation in the vicinity (spatial domino effect), leading to a major devastating accident. The reader interested in domino effects and domino accident prevention is referred to [2–4].

It is obvious that also strong tangible supply chain interdependencies do exist between the installations (and companies) composing a chemical industrial area. Supply chain interdependence is

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not limited to a single industrial area. Natural disasters such as the 1999 Taiwanese earthquake, 2005 hurricane Katrina, 2010 Icelandic volcano eruptions, but also large company accidents (2001 fire in the Phillips semiconductor plant in New Mexico, 2005 Buncefield oil storage depot disaster in the UK, 2010 explosion and sinking of the BP-operated oil rig 'Deepwater Horizon' 50 miles off the US-Louisiana coast, 2011 Japanese earthquake-tsunami disaster, etc.) have illustrated the cascading effects of major disruptions along the supply chain. Different risk events in the supply chain are linked to each other in complex patterns with one risk leading to another, or influencing the outcome of other risks [5] and are therefore intrinsic to supply chain management.

Although most companies tend to develop plans to protect against high frequency, low impact risks in their supply chains and tend to ignore high impact, low likelihood risks [6], disaster and disruption management have received increased attention during the last decade, both from a safety and security and from a supply chain point of view, respectively. Examples of this increased attention can be found in [7–9].

This paper builds upon recent research on domino accident prevention to construct a multi-attribute index for managing safety and security and supply chain related systemic risks. Section 2 provides an overview of current literature. Current safety indices used in safety management in the chemical and process industries are discussed together with state-of-the-art research on supply chain risk management. Compatible network representations are built in Section 3, whereas safety and security-, and supply chain indices for measuring systemic risks are constructed in Section 4. In the Section afterwards, both indices are forged into one user-friendly so-called Systemic Risk Index for comparing and managing systemic risks in chemical industrial areas. An illustrative example is given in Section 6. Section 7 briefly discusses the usefulness of our approach. The conclusions of this article are formulated in Section 8.

## 2. Literature review

### 2.1. Safety and security management literature

Many safety indices have been developed for a number of different purposes in chemical industrial settings. They are extensively used for ranking various chemical installations based on the hazards these installations represent, possibly leading to accident scenarios such as fire, explosions, BLEVE, toxic releases, etc. Well-known examples are the Dow fire and explosion index F&EI [10,11], Dow chemical exposure index CEI [12] and the Mond fire, explosion and toxicity index [13,14]. Other examples include the Accident Hazard Index, which was developed by Khan and Abbasi [15] for the rapid assessment of potential damage caused by accidents in the chemical industry. In 2001, a Safety Weighted Hazard Index was proposed by Khan et al. [16] in which the impact of safety measures on the values of hazard indices was taken into account, leading to a more accurate relative ranking of chemical installations. A predictive safety index based on regular observations of unsafe acts and conditions was developed by Chen and Yang [17] to indicate safety performance in the process industries. Rahman et al. [18] present an overview of inherent safety indices used in process concept evaluation and the authors discuss the pros and the cons of the Prototype Index of Inherent Safety, the Inherent Safety Index, the *i*-Safe index, the I2SI index, INSET ISHE performance indices developed in the INSIDE project, and the EHS method. In 2006, a so-called PROCESO index was proposed by Maroño et al. [19] for evaluating operational safety. Al-Sharrah et al. [20] used accident databases to calculate a safety risk index composed of four terms: frequency of accidents, hazardous effect of the chemical, inventory of the chemical released, and size of the plant. This index can be used for comparing safety risks within a model for petrochemical planning. Leong and Shariff [21] developed an inherent safety index module to assess inherent safety levels during the preliminary design stage. In 2008, Tugnoli et al. [22,23] elaborated a domino hazard index, providing a reference for the analysis of industrial area layout performance.

Our academic journal review of reported safety indices clearly indicates that indices are evolving from calculations where only single installation information is taken into account towards index computations where multiple installations information is ever more employed. However, to the best of the authors' knowledge, none of the developed safety indices so far can be used to evaluate and to compare entire chemical industrial areas and none of them incorporate safety and security, as well as supply chain systemic risks into the index computation algorithm.

### 2.2. Supply chain management literature

There is a wide acknowledgment of risks in the supply chain management literature, which distinguishes between supply, demand, operational and security risks. Building upon the existing literature and the grounded theory applied to in-depth interviews with senior supply chain executives, Manuj and Mentzer [5] define supply risk as *the distribution of outcomes related to adverse events in the inbound supply that effect a firm's ability to meet customer demand* (*both in quality and quantity*) *within anticipated costs and time, or which would cause threats to customer life and safety*. Along the same lines, operations risks relates to the *events that affect the company's internal ability to produce goods and services, quality and timeliness of production and/or profitability* [24]. Demand risk is the *distribution of outcomes related to adverse events in the outbound flows that affect the likelihood of customers placing order with the focal form, and/or variance in the volume and assortment desired by the customer* [25]. The different risk events in the supply chain are linked to each other in complex patterns, with one risk leading to another or influencing the outcome of other risks [5]. Supply chain risk management addresses these issues as reflected in its definition in the well-known SCOR model "the systematic identification, assessment and mitigation of potential disruptions in logistics networks with the objective to reduce their negative impact on the logistics network's performance." [26].

Kleindorfer and Saad [27] distinguish between risks arising from coordinating supply and demand (low impact, high frequency risks) and risks arising from disruptions to normal activities (high impact, low frequency risks).

To be able to optimize systems under uncertainty resulting from the first type of risks, a wide variety of Operations Research approaches such as stochastic programming (recourse models, robust stochastic programming, and probabilistic models), fuzzy programming (flexible and possibilistic programming), stochastic dynamic programming, and robust optimization have been developed (see [28] for a recent application).

Traditional Operations Research approaches seem less suited to handle high impact, low frequency risks. For this type of risks, Kleindorfer and Saad [27] offer a conceptual framework (SAM—Specifying risks, Assessment and Mitigation) that (i) identifies the underlying hazard giving rise to a risk, (ii) quantifies the risks using a risk assessment process that identifies pathways by which the risks may be triggered, (iii) provides guidelines to make assessment and mitigation actions meet the needs of the decision environment. For their SAM approach, Kleindorfer and Saad [27] formulate a set of 10 principles to be simultaneously implemented in an integrated way in industrial practice in order to avoid or decrease disruption risks in (e.g. chemical) supply chains. The approach to manage disruption risks in supply chains is conceptual and does not model or provide a method how to relatively rank such risks.

Marquès et al. [29] provide a complete overview of objectives, approaches and tools of supply chain risk management, the mission of which is defined by the authors as 'the preservation of value through the supply chain'. We refer to the classification of [29] for a study of supply chain risk management more in depth.

However, until present, to the best of the authors' knowledge, supply chain risk management literature does not discuss interdependent supply chain risks, thereby comparing systemic risk behavior within industrial areas and taking safety and security risks into account as well.

## 3. Modeling a chemical cluster as a network

### 3.1. Safety and Security Network (S&S Network)

Reniers and co-researchers elaborated a methodology to represent a chemical industrial area as a weighted directed network for managing knock-on accident prevention. In this section we briefly explain how this approach can be adjusted to set up a safety and security network. For a more elaborate discussion on the methodological foundations of similar networks and applications using empirical data, the reader is referred to [30,31].

In a so-called *weighed graph*, a variable represents the weight of each directed edge (within the graph $G(V,E)$ representing the installations network with $V$ the number of vertices and $E$ the number of edges within the graph). In the safety and security network, the weight of an edge $(v_i,v_j)$ with $v_i \neq v_j$ reflects the amount of danger (for initiating or continuing domino effects) outgoing from installation $v_i$ onto installation $v_j$, and we call this weight the *Domino Danger Unit* (*DDU*) (which is mathematically simply a scalar). Hence, the factor $DDU_{ij}$ is a measure of the danger that installation $v_i$ represents for installation $v_j$ in terms of domino effects. Let $DDU_{ij}$ further denote the weight of an edge $(v_i,v_j)$ with $v_i \neq v_j$, such that $DDU_{ij} \in R^+$ if $v_i \neq v_j$ and $DDU_{ij}=0$ if $v_i = v_j$. If all unidirectional Domino Danger Units between all vertices in the entire network are determined, an installations danger matrix ***DDU*** of order $V \times V$ (with $V$ the number of vertices in the network) is obtained. It should be noted that $DDU_{ij}$ does not have to be equal to $DDU_{ji}$, although the possibility exists.

To develop the DDU, the effect-distance associated with a possible accident scenario from one installation to another is linked to the real distance between the two installations concerned. Depending on the difference in both distances (real distance and effect distance), a standard *distance factor* (*AF*) is defined, using four possible categories. These numerical values represent the relative level of importance given to the pairs of installations with respect to their danger for inducing or continuing domino effects. For a specified accident scenario, if 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 where the real distance strictly exceeds one quarter of the effect-distance and is lower than three quarters of the theoretical effect-distance, $AF=70$. In the final case where the real distance is restricted by the effect-distance and strictly exceeds three quarters of the effect-distance, $AF=40$.

A Domino Danger Unit is then defined to express the escalation dangerousness from one installation to another, by summing the *AF* values for the different possible scenarios $(1,\ldots,K)$ outgoing from installation $v_i$ and incoming to installation $v_j$

$$DDU_{ij} = \sum_{\text{scenario } k=1}^{\text{scenario } K} (AF_{ij})_k \tag{1}$$

This formula is used to calculate the weights of the directed edges $(v_i,v_j)$ and $(v_j,v_i)$ between every pair of installations in a chemical industrial area. The equation allows us to obtain a matrix of domino danger units, mathematically representing the network of the area. It should thus be noted that the *safety and security matrix* is a tabular representation of the domino danger links existing in a chemical installations' network, which we call the *safety and security network*. An illustrative example of such a safety and security matrix and network is given in Fig. 1, representing a chemical industrial area of five installations.

It should be noted that safety and security are two related concepts, which differ in the nature of incidents: safety incidents are non-intentional, whereas security incidents are intentional [32]. Although the two concepts differ, it does not matter for drafting our (safety and security) network: the danger links, whether they are caused by intention or not, if they exist, are used, and the domino danger units are calculated as their weights.

### 3.2. Supply Chain Network (SC Network)

To investigate the supply chain systemic risks of a chemical cluster, we have to establish the weights on the edges linking the vertices (i.e., the chemical installations) in a corresponding supply chain network. It should be noted that the concepts and ideas in this section are applicable to any supply chain, chemical or not. Chemical supply chains are different from non-chemical supply chains mainly in the fact that security is a more important consideration (which is tackled by the S&S Index), but also in the fact that the modal split is not the same in the chemical industry and that an additional transport mode (a pipeline) is available. The lack of flexibility of the pipeline transport mode results in a supply chain that is often very sensitive to disruptions (e.g. there may be no alternative means of transportation for a ruptured pipeline). Since a production plan can only be implemented if a flow of various chemical substances needed are supplied to chemical installations, we consider a supply chain

*Safety and Security Matrix:*

| | | | | |
|---|---|---|---|---|
| 0 | 40 | 70 | 0 | 40 |
| 0 | 0 | 80 | 180 | 210 |
| 140 | 110 | 0 | 0 | 0 |
| 70 | 40 | 210 | 0 | 180 |
| 0 | 40 | 70 | 0 | 0 |

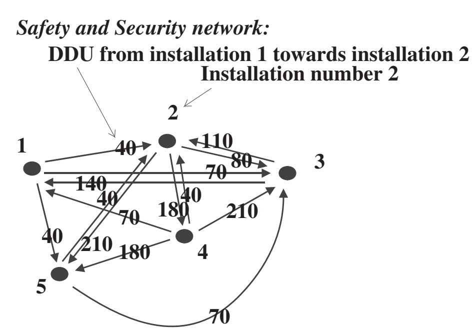


**Fig. 1.** S&S-network of a chemical cluster consisting of 5 installations—an illustrative example.

network of a chemical cluster to consist of chemical installations linked by chemical product flows (thus the edges of the SC Network represent materials flows, whereas the vertices of the SC Network represent chemical installations), ignoring individual company fences in the network. In fact, every chemical installation requires a minimum amount of ingoing products (minimum capacity) and has the possibility to process a certain maximum amount of ingoing products (maximum capacity). Some chemical ingoing products are obviously more crucial and less available than others for the installation to operate properly. Every crucial material input flow of an installation (i.e., one that is absolutely necessary to operate the installation) should evidently be taken into account when constructing a supply chain network. It is very difficult to define or to determine general quantitative cut-off criteria or to make scientifically based recommendations for input- or output flow criteria, since a wide variety of chemical industrial areas exist with very diverging features (sizes, chemicals, flows, etc.). In fact, it would require a large-scale study. Therefore, instead of proposing cut-off criteria, we suggest that the assessor of different chemical clusters first defines crucial input flows and criteria, and then determines quantitative cut-off figures for these criteria, where after the chemical cluster assessment can be carried out.

In fact, we have to determine all contributing factors playing a role in the resilience of the network. The employed factors thus need to provide an indication to what extent the possibility exists that the network may keep functioning ('as normal as possible', and from a supply chain viewpoint) when vertices and/or edges are eliminated from the network.

To this end, different parameters play an important role: (i) the differences between minimum and maximum capacities of materials for an installation (we call these differences the 'deltas' in this paper); (ii) the number of (real) links between two installations in the supply chain; (iii) existing material availabilities from other installations within the considered network (i.e., potential links between installations, which can become real links in case of emergencies); (iv) relevant alternative material availabilities from other installations (the material availability is not present in the network yet, but it may be formed and used, e.g. from another chemical cluster); and (v) the typology of the supply chain wherein the installation is situated: serial or parallel.

The weak points in the supply chain network can for e.g. be identified using the deltas to examine the network. The smaller any delta becomes, the lesser operational flexibility a chemical installation has. A chain reaction of insufficient input- and output flows within the chemical cluster might be the result, leading to substantial threats for the entire cluster. Hence, a delta can be seen as a possible parameter that indicates the resilience of the network. If the most important deltas within a network are determined (by chemical supply chain experts), measures can be taken to ensure that flows can stay operational and thus the systemic risks of the network are decreased. The approach to examine the deltas is best determined by the chemical cluster assessor(s) before carrying out the assessment of the industrial areas.

With regards to the second parameter, obviously the smaller the number of real links composing a supply chain path within the network, the less vulnerable the path is and the more resilient the network is.

If an installation within a path of the network is, for whatever reason, incapable of providing the requested materials to the next installation of the path, it might be possible to obtain the necessary materials from an installation in the network not being part of the initial path (i.e., of the original supply chain), or from an installation, which can be regarded as a relevant alternative, e.g. situated outside the network. The higher the materials' availabilities, present or relevant as an alternative, the higher the potential resilience of the network. An example of this factor is materials stocks. Stocks can be used in the case when links from installations within the network are no longer available.

The typology of a supply chain for a certain material may also be relevant for the resilience of the supply chain. A serial chain is as weak as its weakest link, whereas a parallel chain may be less or more resilient due to multiple input-flows per installation within the chain.

All these parameters have to be assessed and evaluated by supply chain experts having experience with chemical supply chains within and outside the chemical industrial area under consideration. Considering the five aforementioned parameters, experts may assign a score for each existing link between two installations. In order to avoid complexity of the assessment, we suggest to use an ordinal scale with four categories. On a scale from 1 to 4 (1 = may cause disruption to the supply chain with minor financial implications; 2 = may cause disruption to the supply chain with considerable financial implications; 3 = may cause disruption to the supply chain with major financial implications; 4 = disastrous for the supply chain, with huge financial implications) experts assess the implications of each link within the network with respect to the supply chain resilience. Of course, a different ordinal scale can be employed by the assessor. The end result should be a relative ranking of supply chain risks within the network. Hence, for every edge between installation *i* and installation *j*, we obtain a value from 1 to 4 of Supply Chain Risk Factors ($SCRF_{ij}$) based on expert opinion.

This way, we become a network, which is similar to the safety and security network (see previous Section). The supply chain network and its corresponding matrix is illustrated in Fig. 2.

### 3.3. Relationship between S&S Network and SC Network

In Section 3.1, we assume that if separation distances between two installations increase, the risks induced by domino effects decrease. However, this assumption does not take into account the transport risks between these two installations. Nonetheless, risks related to transferring dangerous goods between two

***Supply Chain Matrix:***

| | | | | |
|---|---|---|---|---|
| 0 | 0 | 3 | 0 | 4 |
| 3 | 0 | 2 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 |
| 0 | 2 | 0 | 0 | 0 |
| 0 | 4 | 0 | 0 | 0 |

***Supply Chain network:***

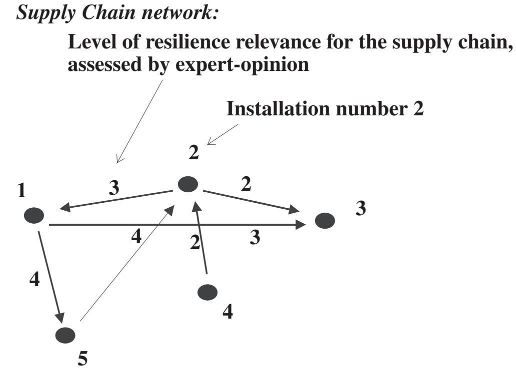


**Fig. 2.** SC-network of a chemical cluster consisting of 5 installations—an illustrative example.

locations should also be taken into account while determining a systemic risk index. Since the S&S Network is solely based on fixed installations and can therefore not take into account 'moving risks', we suggest that such transport risks are considered by the supply chain experts during the assessment of the network's supply chain risks, and would thus be reflected in the SC Network. Obviously, the SC Network's resilience decreases if the transport risk increases, and experts can take this into account when assigning a scale level, for example using information on transport risks calculated by operational risk experts.

Hence, although there is no obvious relationship between the S&S Network on one hand and the SC Network on the other hand, there is some exchange of information necessary for determining both networks.

## 4. Developing indices for both types of systemic risks within chemical industrial clusters

### 4.1. Safety and Security Network Index (S&S Index)

As already mentioned in Section 3.1, the escalation threat that every vertex (installation) poses to every other vertex in the safety and security network can be represented by the Domino Danger Unit associated with the directed edge between every couple of vertices. Therefore, in case of the safety and security network, the network's resilience can be examined by investigating the network's typology using the domino danger units. We thereby assume that each potential path through the network represents a specific risk, i.e., a specific domino effect that may or may not occur. We define the safety and security index of the considered network as the sum of the individual risk indices of all possible paths through the network. The risk index of a path is an aggregated measure of the danger of the individual links on that path. Since a domino accident involving a long path is less likely to occur than a short one, we ensure that the risk index of a path always decreases as the length of the path is increased. Given a path $k$ , the risk index of this path is calculated according to the following equation:

$$SSI_k = \frac{1}{\sum_{ij \in k}(1/DDU_{ij})} \tag{2}$$

From Eq. (2) it can be followed that the higher the *DDU's* of the edges composing the path, the higher the path's risk index. Eq. (2) also ensures that the risk index of a path is always smaller than the risk index of any sub-path thereof. The S&S Index of the network can then be calculated as follows:

$$S\&S\ \text{Index} = \sum_{\text{all paths } k \in G(V,E)} SSI_k \tag{3}$$

The higher the S&S Index, the more dangerous the network. Hence, the S&S Index can be regarded as a relative measure for the safety and security systemic risk.

The number of paths in a network is potentially very large, depending on the sparsity of the graph. If the network graph is complete, i.e., the edge between each pair of vertices exists and has a *DDU* value greater than zero, the number of paths between any pair of nodes is $\sum_{k=2}^{n}(n-2)!/(n-k)!$. As a result, the number of paths in the network is equal to $n(n-1)\sum_{k=2}^{n}(n-2)!/(n-k)!$ [1]

Although all paths can be easily found using a simple recursive algorithm, the number of paths makes this potentially difficult for large networks. In reality however, the network graph will usually be sparse, i.e., many edges will have a weight of zero because there is no possibility of an event at the origin installation to escalate to the destination installation. The speed of calculation of the S&S Index for the network can therefore in most cases be significantly increased by realizing that a path containing any edge with zero weight will always have an *SSI* of zero. The algorithm that was used, is given in Appendix A.

For networks in which even the enhanced recursive procedure is unable to found the complete network S&S Index, we define the S&S Index at level $l$, in which we only consider paths of length $l$ or smaller

$$S\&S\ \text{Index}^l = \sum_{\text{all paths } k \text{ of length} \leq l} (SSI_k) \tag{4}$$

This index can be efficiently calculated up to values of $l=5$, even for very large networks. The index at level $l$ will always be smaller than the index at level $m$ for $l<m$. It is recommended when comparing networks to calculate the *SSI* for the different industrial areas at the same level.

For our five-node illustrative example network from Section 3.1, the S&S Index at level 5 becomes 4624.75. The S&S Index at levels 4, 3, and 2 is ,respectively, equal to 3786.25, 2738.97, and 1480.00. It is easy to understand that this final value is the sum of all individual $DDU_{ij}$ values in the network.

### 4.2. Supply Chain Network Index (SC Index)

The Supply Chain Network Index is defined in a similar way as the S&S Index. Again, we assume that any path from a node to another node represents a potential danger in the network and that all possible paths need to be considered in order to calculate a measure of the total risk involved. For a single path $k$, an SCI can be calculated from the individual Supply Chain Risk Factors ($SCRF_{ij}$) on the edges as follows:

$$SCI_k = \frac{1}{\sum_{ij \in k}(1/SCRF_{ij})} \tag{5}$$

Since the longer the path of installations linked by supply chain links, the smaller the probability of its existence, hence the smaller the path's index, which is consistent with the index results. The SC Index for the entire network becomes:

$$\text{SC Index} = \sum_{\text{all paths } k \in G(V,E)} SCI_k \tag{6}$$

Similar to the S&S Index, the SC Index can be calculated up to a certain level $l$ as follows:

$$\text{SC Index}^l = \sum_{\text{all paths } k \text{ of length} \leq l} (SCI_k) \tag{7}$$

The index provides a measure of the level of a supply chain network's resiliency: the higher the index, the less resilient the network. In other words, the SC-Index can be regarded as a relative measure for supply chain systemic risk.

In case of the illustrative supply chain network from Section 3.2, the SC Index at level 5 becomes 32.333. The SC Index at level 4 is also 32.333 (indicating that there do not exist any paths of length 5), which can be easily verified in Fig. 2. Further, the SC Index at levels 3 and 2 is equal to 28.462 and 18.000, respectively.

[1] A proof of this formula is straightforward. To find the number of paths of length $k \geq 2$ between two arbitrary vertices 1 and 2, it suffices to see that any permutation of $k-2$ vertices from the remaining $n-2$ (i.e., all vertices except 1 and 2) can be inserted between vertices 1 and 2 to form a valid path. The number of paths of length $k$ between vertices 1 and 2 is therefore equal to $P_{k-2}^{n-2} = (n-2)!/(n-2-k-2)! = (n-2)!/(n-k)!$. The number of paths of all possible lengths between vertices 1 and 2 can be found by summing this value from $k=2$ to $k=n$ , i.e., $\sum(n-2)!/(n-k)!$. The number of paths between any pair of vertices can be found by multiplying this value with the number of node pairs $n(n-1)$.

## 5. Multi-attribute model for comparing and ranking chemical clusters with respect to systemic risks

Investigating the safety and security network's and the supply chain network's typologies allows us to develop a systemic risk picture for both types of networks.

By using both the S&S Index and the SC Index, we can compare the behavior of different network configurations, and e.g. increase the reliability of supply chain key input flows by introducing redundancies, or decrease domino effects risks and threats by improving safety and security countermeasures.

It should be noted that these index-values are not absolute values. Hence, it is not possible to determine an industrial area unambiguously to be characterized by 'absolute systemic risk level *X*'. However, using these indices we are able to rank industrial areas and make recommendations to increase the robustness of chemical industrial areas towards their safety and security and supply chain systemic risks within the industrial area. A possible extension of the multi-attribute model developed in this paper would be to include other measures of supply chain performance besides risk-related ones, e.g., measures of the sustainability of the supply chain.

Furthermore, both indices can be employed to develop a model for prioritizing chemical industrial areas with respect to their overall systemic risks. By doing so, we have to realize that we want to create a relative measure giving us an indication of the overall resilience of a network of chemical installations. From a supply chain perspective, a relatively low SC-Index indicates the network to be somewhat resilient for supply chain systemic risks compared with other networks. From a safety and security viewpoint, a relatively low S&S Index leads to a network which is, compared to other networks, made safe and secure for the escalation of accidents.

Systemic risks of a chemical cluster, then, are a function *F* of their S&S Index and SC-Index as represented by:

$$\text{Network Systemic Risk} = F(S\&S\ \text{Index, SC Index})$$

Recognizing this relationship, analyzing and prioritizing systemic risks must take the S&S Index and the SC Index into account, regardless of whether ordinal or value function formalisms are used. An ordinal approach to rank systemic risks would be based on a procedure that 'bins' these risks into S&S Index and SC Index categories. Ordinal procedures are a valid but high-level way to analyze and rank-order risk events. In our case, we should recognize that the indices can only be used in a relative way (for comparing one industrial area against another industrial area) and therefore an ordinal scale procedure would be most appropriate. However, arithmetic operations on the ordinal numbers representing these indices are not permissible.

Therefore, we use a well-known algorithm, which is mainly used in voting problems [33,34]. The algorithm is known as the Borda Algorithm [35]. The Borda rule assigns linearly decreasing points to consecutive positions, e.g. for three alternatives the points would be 2 for the first place, 1 for the second place, and 0 for the third place. The Borda algorithm can be found in literature on group decision making and social choice theory. Readers interested in applications of the algorithm are referred to [36–38]. The algorithm is employed to develop an ordinal ranking of preferences. The Borda rule can also be employed in a risk management context [39,40]. We use the Borda Algorithm in this article to develop an ordinal ranking of chemical clusters, thereby using both the S&S Index and the SC Index.

It should be noted that, if an installation was to be destroyed, the supply chains of all paths where this installation was part of (materials are provided to – or demanded from – other installations within the network), are affected as well. Hence, besides the consequences for safety and security, the S&S Index has an impact on the supply chain resiliency of the network as well. Since the S&S Index has an impact on the supply chain resiliency of the network (and not only on the safety and security resiliency of the network), this S&S Index may be regarded as more important for decreasing systemic risks than the SC Index, and therefore a different point-system is used in both cases.

In our systemic risk management context, we suggest the algorithm to work as follows. All chemical industrial areas, which are studied, are ranked by both the S&S Index and the SC Index. If there are $n$ chemical industrial areas to be compared, then the first-place area receives $n$ points for the S&S Index and $(n-1)$ points for the SC Index, the second-place area receives $(n-1)$ points for the S&S Index and $(n-2)$ points for the SC Index, and so forth. The area ranked last receives 1 point (S&S Index) and 0 points (SC Index). The points are summed across all areas and the industrial area with the most points is ranked first, etc.

Next, let us apply this concept e.g. in case of four clusters: *C*1, *C*2, *C*3, and *C*4. Suppose (from calculating the S&S Index and the SC Index) that the rank-order positions are as follows:

$$\text{S\&S-Index}: C3 \succ C2 = C1 = C4$$

$$\text{SC-Index}: C1 \succ C3 = C2 \succ C4$$

When ties occur, e.g. in case of the SC-Index *C*2 and *C*3 are tied, points allocated to these positions are derived from the average; that is, *C*2 and *C*3 each will receive $((n-2)+(n-3))/2$. In case of the S&S Index *C*1, *C*2, and *C*4 each will receive $((n-1)+(n-2)+(n-3))/3$.

The resulting point distribution is summarized in Table 1.

From Table 1, we conclude that chemical industrial area number 3 (*C*3) has the highest Borda count and, therefore, ranks first. The overall rank-order of all four chemical clusters employing both indices is as follows: $C3 \succ C1 \succ C2 \succ C4$.

The sole concern of our developed approach is the investigation of a chemical industrial area's position relative to other industrial areas if we look simultaneously at supply chain systemic risks and safety and security systemic risks within these areas. This ranking information may lead to optimizing the allocation of safety and/or security resources for prevention, mitigation and protection measures within chemical industrial areas throughout regions and/or countries.

Consider a chemical industrial area network exhibiting a relatively high SC-Index and/or S&S-Index, compared with other chemical clusters within a region. The former area thus needs attention from the viewpoint of systemic risk behavior. To decrease the systemic risks, preventative measures can be focused on installations, which are identified to be important for contributing to the index or indices. The importance of the installations can be determined by examining the different parameters contributing to the indices. If local rearrangements within the network are made (i.e., installations highly contributing to the networks' vulnerability are more secured e.g. by protecting them better, by introducing redundant material flows, by ensuring material availability, etc.),

**Table 1**
Ranking chemical clusters using the Borda Algorithm for a 4-cluster illustrative example.

| | *Chemical clusters* | | | |
|---|---|---|---|---|
| | ***C*1** | ***C*2** | ***C*3** | ***C*4** |
| ***S&S Index*** | 2 | 2 | 4 | 2 |
| ***SC Index*** | 3 | 1.5 | 1.5 | 0 |
| **Total** | **5** | **3.5** | **5.5** | **2** |

then global network consequences do follow suit (i.e., systemic risks diminish). Furthermore, to obtain deeper insights into the chemical cluster conditions determining the vulnerability towards both types of systemic risks, factors such as the number of installations involved, the distances between the installations, the precautions taken on the installations, the type of chemical substances transported, the number of input flows per installation, the number of output flows per installation, the number of redundant input and output flows per installation, the size of the area, etc. can be further investigated. Information can be gathered by a so-called Multi-Plant Council [41,42]. This way, this supra-company organization can deal with an industrial area's systemic risks.

Let us now consider an illustrative example of four (hypothetical) industrial areas (and their hypothetical networks) to be compared and ranked for their systemic risk behavior in the next Section.

## 6. Illustrative example

In this section, we show the usefulness of the developed method by applying it to a (hypothetical) example. To this end, we have artificially generated the data for four hypothetical chemical clusters. The data have been generated in the following way. First, we generate the installations randomly on the Euclidean plane between (0,0) and (1000,1000). All distances are calculated and normalized between 0 and 1 (dividing by $1000 \times \mathrm{sqrt}(2)$). Since the distance between two installations determines to a large extent their interconnectedness and the risk they pose for each other, this normalized distance is a factor in the generation of *DDU* or *SCRF* values. We define a parameter ss_factor and a parameter sc_factor and generate the *SCRF* and *DDU* values as follows. To generate the *DDU* value between two facilities, the normalized distance is multiplied with ss_factor and the resulting value is the probability of a link receiving a *DDU* value greater than zero. If the link should receive a *DDU* value greater than zero, it is generated as a random number, uniformly distributed between 0 and 500. To generate the $SCRF_{ij}$, a similar procedure is followed (using sc_factor instead, and generating a random value between 1 and 4 instead of 0 and 500).

We have artificially generated four clusters *C*1, *C*2, *C*3, and *C*4. The data used to generate these clusters are shown in Table 2. The parameter values were chosen in such a way that the final results are comparable.

All indices are calculated at level 5. The calculated indices are shown in Table 3.

**Table 2**
Parameters used to generate the hypothetical chemical clusters *C*1, *C*2, *C*3, and *C*4.

| | *Installations* | *ss_factor* | *sc_factor* |
|---|---|---|---|
| **C1** | 5 | 5 | 10 |
| **C2** | 30 | 0.2 | 0.5 |
| **C3** | 35 | 0.1 | 0.4 |
| **C4** | 80 | 0.05 | 0.01 |

**Table 3**
Calculated indices for the four hypothetical clusters.

| | *S&S Index* | *SC Index* |
|---|---|---|
| **C1** | 22,262.9 | 9414.99 |
| **C2** | 37,884.4 | 6228.48 |
| **C3** | 20,907.6 | 7273.92 |
| **C4** | 76,241.3 | 2569.69 |

**Table 4**
Borda scores for the hypothetical example.

| | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|
| ***S&S Index*** | 2 | 3 | 1 | 4 |
| ***SC Index*** | 3 | 1 | 2 | 0 |
| ***Total*** | 5 | 4 | 3 | 4 |

The subsequent Borda counts can be found in Table 4.

Hence, Table 4 indicates that in the case of our four-cluster hypothetical example, Cluster *C*3 is the safest with respect to systemic safety and security risks and systemic supply chain risks, whereas cluster *C1* is the least safe: $C1 \succ C4 = C2 \succ C3$.

## 7. Conclusions

To investigate the systemic risk features of a cluster network, an industrial area is considered as a graph and is represented by its safety and security matrix and by its supply chain matrix. Subsequently, the Safety and Security Index and the Supply Chain Index of the network are calculated and the Borda algorithm is used to determine the relative position of chemical industrial areas with respect to their systemic risk behavior. This way, a mathematically sound methodology is developed to map both types of systemic risks in chemical industrial areas. Using the model results, conclusions can be drawn about possible prevention measures to lower the systemic risks.

Using the proposed model, we can thus investigate whether systemic risks might be prevented in a more rational way. For example, by ensuring the continuity of certain (essential) material flows between installations, the risks of supply chain failures (supply chain systemic risks) are lowered and the production reliability of the entire chemical cluster network is improved. Similarly, adequate precautions at a limited number of well-chosen installations (determined by our elaborated model) can cut important accident escalation links in the network, making the overall chemical cluster against the propagation of knock-on accidents more secure against safety and security systemic risks.

However, the efficiency and effectiveness of protection measures against systemic risks depend largely on the network topology of the chemical cluster. Efficiently preventing and protecting systemic risks and efficiently mitigating their consequences in an industrial area is only possible by considering the area as a whole. Although there appear to be countless possibilities as to what might go wrong in a chemical cluster and what the industry might have to do to protect against systemic risks, this article offers new insights into tackling this risk challenge.

## Appendix A. Algorithm description

In this appendix, we describe the algorithm to calculate both the Safety and Security Index (S&S Index) and the Supply Chain Index (SC Index). The former is calculated based on the domino danger units between two installations ($DDU_{ij}$), whereas the latter uses the supply chain risk factors ($SCRF_{ij}$). Because the algorithm is completely similar for the S&S Index and the SC Index, we assume a general 'risk' between two installations and use the symbol $r_{ij}$. The algorithm is recursive and calls a function next_level to calculate the total risk for a path with one installation more than the previous path.

```
function next_level (previous_installations);
  begin
  if (previous_installations.size ≥ 2) then
```

```
    calculate total_risk for all facilities in the vector
    previous_installations;
    add this risk to total_network_risk;
  end if
  if (previous_installations.size < l) then //comment: only
  calculate up to level l
    if (total_risk > 0) then //comment: only continue paths that
    have total_risk > 0
          for (all installations f)
                if f is no element of previous_installations then
                        create pf=previous_installations;
                        add f to pf;
                        next_level (pf);
                end if
          end for
    end if
  end if
end function;
```

**Algorithm.** Calculate total network risk index (S&S Index or SC Index) at level *l*.

```
Input: r_ij: risk factor between each pair of installations
Output: Total network risk index
total_network_risk=0;
read data;
pf=empty; //comment: the vector pf contains the installations
that are visited on a path
next_level (pf);
return total_network_risk;
end;
```

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