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A method for risk modeling of interdependencies in critical infrastructures

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ABSTRACT

Failures in critical infrastructures may be hazardous to population, economy, and national security. There can be strong interdependencies between various infrastructures, but these interdependencies are seldom accounted for in current risk and vulnerability analyses. To reduce probability and mitigate consequences of infrastructure failures, these interdependencies have to be assessed. The objective of this paper is to present a method for assessing interdependencies of critical infrastructures, as part of a cross-sector risk and vulnerability analysis. The method is based on a relatively simple approach applicable for practitioners, but may be extended for more detailed analyses by specialists. Examples from a case study with the Emergency Preparedness Group of the city of Oslo, Norway, are included.

1. Introduction

Critical infrastructures are technological networks, such as energy supply, transport services, water supply, oil and gas supply, banking and finance, and ICT (information and communication technology) systems [1,2]. These systems are important to maintain essential functions of society, and infrastructure failures can cause serious harm to population, economy, and national security. Critical infrastructures interact at different levels, and failure in one infrastructure may impact the functionality of other infrastructures [3]. The significant societal importance of these infrastructures and their entanglements means that sufficient safety and security measures should be identified to reduce the risks of failure [4,5].

In the early 1990s, a simple approach to quantitative risk analysis was developed in Norway, called Risk and Vulnerability Analysis (RVA; in Norwegian, ROS—"Risiko- og Sårbarhetsanalyse"), [6], which is rather similar to Preliminary Hazard Analysis (PHA) [7]. Risk analysis methods, like Probabilistic Safety Analysis (PSA) and Quantitative Risk Analysis (QRA), comprise detailed probabilistic and physical models. Such models require more knowledge and resources than normally available in small/medium enterprises and the public sector, and the RVA has become a frequently applied approach. During the last two decades, the RVA has been applied for various critical infrastructures separately, but not as a unified approach across sectors, including interdependencies between the various infrastructures.

The objective of this paper is to present a method for modeling and assessing interdependencies between critical infrastructures, as part of an overall cross-sector extended RVA developed in the DECRIS project [8]. The paper builds on a simplified approach that was presented in Ref. [9], but explains and discusses the method more thoroughly, and introduces more advanced calculations of risk. The method is illustrated by examples from a case study of the city of Oslo, Norway. The case study was carried out in cooperation with the Emergency Preparedness Group (EPG) in Oslo. The EPG is an organization working with safety and cooperation between the critical infrastructure owners of water supply, electricity supply, ICT, hospital, harbor, transportation, and fire and rescue services in the municipality. Previous RVA-analyses of Oslo [10,11] were used as a basis for the case study. The results are now being used as input to the work on societal risk carried out by the EPG of Oslo, and as basis in the planning of future research projects.

The structure of the paper is as follows. Section 2 gives a short overview of terms, characteristics, and some approaches to interdependency analysis suggested in the literature. The purpose is to clarify some important issues related to the proposed approach in the present paper, but not to give the reader a total overview of all existing methods. Section 3 describes the suggested approach to analyzing interdependencies as part of an overall risk analysis of critical infrastructures. Section 4 presents the discussions and conclusions.

2. Types of interdependency analyses

There are different ways of defining and characterizing interdependencies. Sometimes it may be useful to distinguish between

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dependencies and interdependencies. Setola et al. [3] use direct dependencies, which are relatively easy to identify, model, and analyze, and interdependencies, which are mutual dependencies that may be dangerous, but hard to understand. Rinaldi et al. [1] define interdependencies between infrastructures as a bidirectional relationship and dependencies as unidirectional. Bidirectional relationships means that the state of one infrastructure affects or is correlated according to the state of another infrastructure. Unless referring to the work of other authors, the term interdependency is used in this paper, meaning that the dependency can be either unidirectional or bidirectional (so it is not necessary to specify the "causal direction" of the dependency). In other words, dependencies may exist between infrastructures, within an infrastructure itself, and may include "loops", for example, in terms of one infrastructure causing degradation of another one, which again causes additional degradation in the first one.

Johansson and Jönsson [12] propose to distinguish between direct (first order) or indirect (second order; inter) dependencies. If, for example infrastructure i depends on infrastructure j, and infrastructure j depends on infrastructure k, there is a second order (indirect) dependency between i and k. Obviously, indirect dependencies may be more difficult to spot than direct. Zimmerman [13,14] distinguishes between spatial and functional interconnectedness and dependency. Spatial interconnectedness refers to proximity between infrastructures as the most important relationship between the systems. Functional interconnectedness refers to a situation in which an infrastructure is necessary for operation of another infrastructure, for example, the pumps in a water treatment system needing electricity in order to function. There are also situations with both types of interconnectedness. The types of interdependencies addressed in this paper resemble Zimmerman's spatial and functional categories.

In addition to the different definitions of terms and characteristics, several attempts have been made to model infrastructure interdependencies. According to Johansson and Jönsson [12], there are in general two types of approaches for dependency modeling/analysis—the empirical approaches and the predictive approaches. In empirical approaches, previous events may be studied in order to increase the understanding of infrastructure interdependencies. Often, the purpose is to find patterns that may be interesting with respect to political decisions. It can, for example, be patterns related to the consequences for the society, or how often failures propagate between the various infrastructures. Examples of empirical approaches are Refs. [2,15–17].

The predictive approaches model or simulate the behavior of a group of coupled infrastructures, for example, to assess how disturbances cascade through the systems. Examples of predictive approaches are Refs. [12,18–20]. The proposed approach in this paper belongs to the group of empirical approaches. The main focus is on the consequences of cascading failures in critical infrastructures (not on the causes), and calculations of risks. Both the predictive and empirical methods may be valuable as input to RVA, but few are explicitly integrated in practice.

3. Method for modeling and analysis of infrastructure interdependencies

An extended cross-sector RVA for critical infrastructure [9,21] consists of the following two phases:

- Phase 1—a standard RVA, identifying and analyzing hazardous events. This is rather similar to a preliminary hazard analysis (PHA) [7], and risk is usually assessed using risk matrices. Also a risk screening is carried out to identify the hazardous events for which more detailed analyses are carried out.
- Phase 2—detailed analysis of selected hazardous events, e.g. to analyze interdependencies.

The focus of this paper is on phase 2. Based on the results from phase 1, some hazardous events should be selected for interdependency analysis. This could be based on decision criteria, such as high risk, serious consequences, or suspected strong interdependencies.

In the case study (involving electricity supply, water supply, transport, and ICT) the following four events were selected as a result of the risk screening in phase 1 (the selection process is described in Ref. [21]):

1. loss of electricity supply (main transformer stations/regional grid);
2. loss of main water supply from Maridalsvannet;
3. fire/explosion at Sjursøya (major petroleum transportation terminal); and
4. culvert/joint conduit event

Event 4, involving short-circuiting in a culvert with electricity and ICT cables, was used to illustrate the method for modeling interdependencies and analysis of risks. (For analysis of event 1, see Ref. [22].)

The method for analyzing interdependencies includes the following steps:

1. Describe the initiating event.
2. Identify interdependencies. Perform qualitative analysis.
3. Perform a semi-quantitative assessment of the risk of the scenario.
4. Perform a detailed quantitative analysis of interdependencies (optional)
5. Evaluate risk and measures to reduce interdependencies.
6. Cost/benefit analysis (optional).

The remaining part of this section is structured according to these steps.

3.1. Step 1—describe initiating event

To be able to identify and analyze the interdependencies, the selected event(s) have to be described in detail. This means that physical location, environmental conditions and constraints, spatial and temporal scales, technical and organizational systems, operating factors, and physical objects affected immediately should be described.

The next task is to elaborate on the societal critical functions (SCF). This is related to the involved physical objects, organizations, and social structures, including their state before, during, and after the initiating event. The term societal critical function is used in this paper to represent the function(s) of the critical infrastructures. One critical infrastructure may have one or more SCFs. Possible causes to the initiating event have to be included, in order to determine how the consequences depend on the causes.

In the case study, the culvert event was specified as follows:

- "Loss or damage to electricity supply and/or ICT systems close to a culvert at Oslo Central Station (railway station), with cascading failures to other SCFs".

The basis for the initiating event description was a real event that occurred at Oslo Central Station in November 2007, when an entrepreneur unwarily broke a cable when digging a ditch. The cable break led to short circuit and fire at the Oslo Central Station, which paralyzed the region's rail traffic and transportation systems for 20 h, and the internet systems for about 10 h [23]. The culvert example is not used for accident investigation into what actually happened that day, but more or less as a starting point for analyzing interdependencies in the possible chain of events of such a scenario.

The layout of the electric cables in the culvert at Oslo Central Station is shown in (Fig. 1, based on Ref. [23]. There were two high-voltage cables, which served three net stations. The redundant cables were placed in the same culvert. In the actual fire, both cables were destroyed. The physical objects, systems, and infrastructures affected immediately were electricity supply cables and ICT cables (telephone, internet, and railway communication). The culvert is in close proximity to the railway station at Oslo Central Station, major road trafficking intersections and highways, a subway station, and a bus station. The traffic control station for a large part of the Norwegian railway traffic is located in the railway station, and this station receives electricity supply from one of the three net stations that was affected.

3.2. *Step 2—identify interdependencies and perform qualitative analysis*

Interactions and couplings between the infrastructures will strongly affect the extent and consequences of an initiating event. An interdependency analysis may focus on interdependencies (i) between the causes of the event, and/or (ii) between the infrastructures, which come as a result of the consequences (cascading effects) of the initiating event itself. The latter is the main focus in this paper.

In the proposed approach to the modeling and analyzing interdependencies, two categories are of main interest

1. location-specific (physical) interdependencies and
2. functional interdependencies

After having identified the SCFs relevant for the culvert event, location-specific interdependencies between these may be revealed by asking

- Is the SCF directly threatened by the initiating event due to the (physical) location of its systems/equipment?
- Are there other locations/functions that can be threatened, e.g. by spreading of a fire/smoke? What is the probability of still being able to supply customers with electricity?
- Are there barriers between the SCFs (possibly reducing the extent of the event)? Are there barriers able to resist cascading failures?
- What consequences are likely?

Examples of relevant location-specific interdependencies in the culvert scenario were as follows:

- Cables in the culvert contribute to interdependencies between electricity supply and ICT.
- During the actual event at Oslo Central Station, smoke spread from the fire in the culvert to the departure/arrival hall at the railway station, causing the station to shut down. This illustrates interdependency between electricity supply/ICT and railway transportation.
- Relevant barriers in the case study were
  - physical protection of cables,
  - access control (with respect to sabotage),
  - redundancy of electricity supply, and
  - physical separation of the different affected SCFs.

Next, the functional interdependencies can be identified by asking

- Which SCFs are directly affected by the location-specific interdependencies?
- Which SCFs are further affected by the functional dependencies?

Examples of relevant functional interdependencies for the culvert event were

- Important phone systems require electricity supply, which means that there is interdependency between electricity supply and ICT.

To visualize and communicate the interdependencies to the stakeholders, a "cascade diagram" is introduced. A simplified diagram is shown in Fig. 2. A cascade diagram gives an overview of the interdependencies in a structured manner, and represents the accident scenario. In this paper, the terms "initiating event" and "accident scenario" represent different concepts, in accordance with Ericson II [7], who define an accident scenario as a "series of events that ultimately result in an accident. The sequence of events begins with an initiating event and is (usually) followed by one or more pivotal events that lead to the undesired end state".

The cascade diagram resembles an event tree, but focuses on consequences in terms of interdependencies. There are also some differences in the quantification of risk (which will be described later in this section).

In Fig. 2, the initiating event can directly affect three SCFs due to location-specific interdependencies, ("node" SCF 1–3). Here

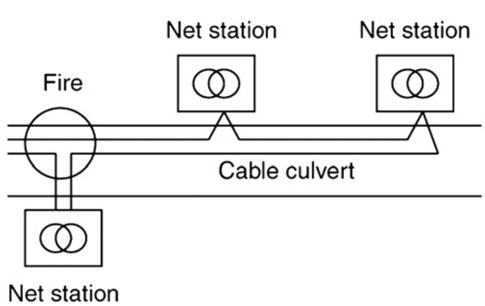

Fig. 1. Electric cables in culvert [23].

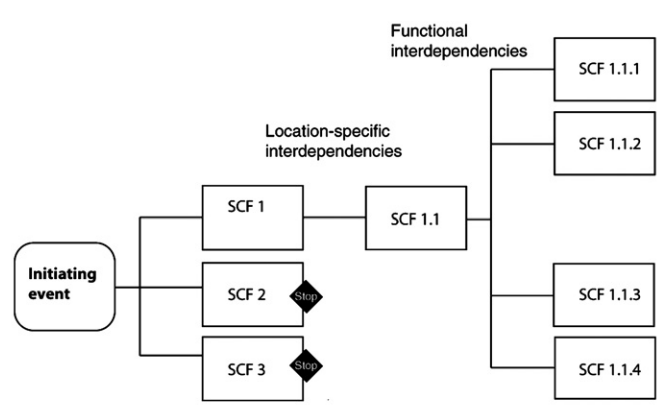

Fig. 2. Example of a cascade diagram.

SCF2 and SCF3 are not further investigated, but from SCF 1, four functional interdependencies have been identified.

The construction of a cascade diagram starts with the initiating event (to the left in the diagram), and places the affected SCFs, representing location-specific interdependencies, to the right. The SCFs related to the functional interdependencies are then introduced (rightmost part of Fig. 2). When interdependencies and consequences further out in the chain of events are revealed, the cascade diagram is expanded. The interdependencies are visualized by lines, and the boxes represent the affected SCFs. If a SCF is not investigated any further, the box is marked with a "stop symbol". The boxes without subsequent SCFs to the right in the diagram are marked with a dashed line (Fig. 2), and these are called leaf nodes.

The cascade diagram supports both a qualitative and quantitative analysis of consequences and risk, which is useful when stakeholders without a strong background in risk analysis are involved. After having identified the interdependencies to a feasible level of detail, they may be evaluated qualitatively by discussing and documenting the risks that appear in the cascade diagram (Fig. 2). Then the purpose is to determine whether they have major accident potential, if interdependencies should be reduced, and if there are needs for risk reducing measures. In some cases, it may be relevant to investigate those interdependencies with the highest probabilities only, and as such, simplify the diagram.

The coupling and response behavior of the SCFs can be investigated qualitatively by considering questions like

- Does the interdependency cause a total or partial malfunction of the SCFs?
- Are there available barriers that can prevent the occurrence of the cascading failures?
- What are the likely consequences due to loss of the various SCFs?

3.3. Step 3—perform semi-quantitative assessment of risk of scenario

In order to assess the risk of the culvert scenario more quantitatively, we define risk to be the product of frequency and consequence, $R=fC$. The following measures (parameters) are introduced:

- frequency (F),
- probability (P),
- extent (E), i.e. the number of people being affected by unavailability of a SCF, and
- duration (D), i.e. the time period (h) in which a SCF is unavailable.

The frequency measure, F, may be used for the initiating event (e.g. number of times the initiating event occurs per 100 years). Conditional probabilities, P, are applied to describe the subsequent events, given that the previous event(s) has occurred. These conditional probabilities depend on the extent, E, and duration, D, of the previous event or node in the cascade diagram. In Fig. 2, this means that determining the probability of, for example, SCF 1.1 being affected should be based on assessing the extent and duration of SCF 1. A long duration and a high extent of impact on SCF 1 may increase the probability of SCF 1.1 being affected.

The risks may then be analyzed semi-quantitatively, applying categories for F, P, E, and D. (Table 1 shows five categories defined for each of the parameters used in the case study, but these categories have to be determined based on the goal and scope of the problem at hand. The categories in Table 1 were used for the calculations of risks in the culvert scenario.

Table 1
Categories for F, P, E and D used in case study.

Categories	Frequency (f)	Probability (p)	Extent (e)	Duration (d)
1	Less than once every 1000 years	10^{-3}–10^{-4}	10	<1 h
2	Once every 100–1000 years	10^{-2}–10^{-3}	100	1 h–6 h
3	Once every 10–100 years	10^{-1}–10^{-2}	1000	6 h–48 h
4	Once every 1–10 years	1–10^{-1}	10,000	48 h–1 week
5	Once or more every year	1	100,000	>1 week

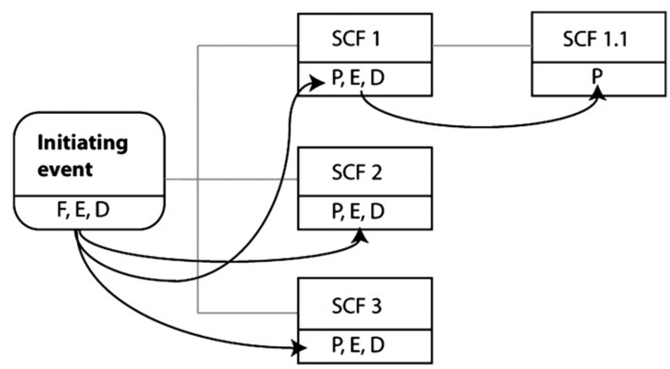

Fig. 3. Probability of an event in cascade diagram is given by extent and duration of previous event.

In Table 1, category 1 represents the least serious category; those with a frequency (f) of less than once every 1000 years, a probability (p) in between 10^{-3}–10^{-4}, the extent (e) being 10 affected persons, and the duration (d) less than 1 h. Category 5 represents the opposite, the most serious outcomes.

The next step of the semi-quantitative analysis is to estimate the risk triplet $\langle F, E, D\rangle$ of the initiating event, and $\langle P, E, D\rangle$ of each subsequent event (or node) in the cascade diagram, shown in Fig. 3. The values of E and D will affect the probability category P of a subsequent event (to the right). When these are established, calculations can be carried out from right to left in the cascade diagram, starting with the leaf nodes, and ending with the risk estimate of the initiating event. In other words, the quantification starts from the left hand side in the cascade diagram and goes to the right, before the calculations can be carried out from the right hand side of the diagram to the left hand side.

Since the categories in Table 1 are given on a logarithmic scale, it is useful to transform these categories into corresponding "real values" in order to quantify risk. The transformations can be carried out using Eqs. (1)–(7) below. The actual frequency of the initiating event is given by

$$f=10^{F\text{-}4.5} \tag{1}$$

The justification for Eqs. (1), (2), and (4) is based on the geometric average values of the categories. This means that, for example, using $F=2$, $f=0.00316$ is attained, which corresponds to the geometric mean (1/316) of that category.

The conditional probability of a subsequent event equals

$$p=10^{P\text{-}4.5} \tag{2}$$

for $P=1, 2, 3, 4$. If $P=5$, then $p=1$ (Table 1).

The extent, e, is given as

$$e = 10^{E} \tag{3}$$

Category $E=1$ in Table 1 represents 10 affected persons, whereas category $E=4$ means that 10,000 persons are affected.

The following equation applies for duration:

$$d = 6^{D-1.5} \tag{4}$$

This is based on the duration categories in Table 1. For example, $D=4$ gives $d=88.2$ h, which is approximately (≈ 89.8) the geometric mean of the category.

In order to calculate the consequences and the risk of the initiating event, the calculation procedure starts with the leaf nodes, shown in Fig. 4. For each leaf node, j, having probability P_j, the expected consequence C_j related to this leaf node is given by

$$C_j = 10^{P_j\text{-}4.5} \times 10^{E_j} \times 6^{D_j-1.5} \tag{5}$$

When the mean consequences for all leaf nodes have been calculated, these consequences are merged for every branch into the corresponding merging node to the left, (e.g. SCF 1.1 in Fig. 4). When the risk related to the merging node is calculated, this is based on the consequences, C_j of the branch nodes and the probability, P_i for the merging node, i (here SCF 1.1) of the branch. In other words, the consequences for each branch are summed, and then multiplied with the transformed probability measure of its merging node:

$$C_i = 10^{P_i\text{-}4.5} \times \sum_j C_j \tag{6}$$

This process is repeated, and finally the mean consequence of the "initiating event" can be calculated, giving the total risk of the accident scenario

$$R = 10^{F-4.5} \times \sum_k C_k = fC \tag{7}$$

Here the summation is over all k, corresponding to the location-specific interdependencies, i.e. $k=1$, 2, 3 in Fig. 5.

In short the procedure means that one moves from left to right when frequency and probabilities (based on likely extent and duration) are assessed. Then, one moves from right to left when expected consequences are calculated. Barriers that may be present are assessed and their effects are included in the E and D of the nodes. At last, the total risk $R=fc$ is calculated, from the frequency, f (Eq. (1)) and the consequence, $C=\sum_k C_k$. In the present numerical example R represents the expected number of person hours of lost service per year.

The culvert scenario was analyzed semi-quantitatively, and for illustration the calculations and results are shown in Fig. 5. The risk, using the categories in Fig. 5, is estimated to 631 person hours per year. Here, some nodes are allocated probability category $P=5$, (which gives $p=1$), due to couplings between the nodes, e.g. between the train communication and railway transport. If train communication fails, then the railway transport is affected, regardless of extent and duration.

In the cascade diagram in Fig. 5, the relevant SCFs are specified and coupled to their physical objects, i.e. cables and departure/arrival hall, since these objects are affected immediately. In general, it is important to consider possible traffic junctions, traffic control centers, and transportation means in proximity of the culvert. Next, failure in the electricity supply cables was assessed, which in this case may affect the electricity supply (with some probability). This is the transition from location-specific interdependencies to functional interdependencies (failure of the cables (location-specific) to loss of electricity supply (functional)).

The procedure described above treats all SCFs as equally important. However, it is straightforward to emphasize that failures of some SCFs are more important than others using weighting factors, as shown in Ref. [9]. In addition, combined effects can be taken into account. Loss of more than one SCF may affect another SCF, which may be a more serious situation than simply just adding the losses of the two SCFs (when they fail separately). One way to treat such combined effects is to increase the "extent" measure, E. A rough approach would be to increase all extent measures, Ej, with one unit for events with relevant combined effects. If these effects are strong, Ej could be increased by two units, and so on. A numerical measure for the combined (non-additive) effects could then be established by calculating the risk measures for the initiating event with and without treating the combined effects. The ratio between these two risk measures will give a quantitative expression of the strength of the non-linear combined effect.

3.4. Step 4—perform detailed quantitative analysis of interdependency (optional)

If more information is needed, a detailed quantitative analysis may be carried out using values instead of the categories in the

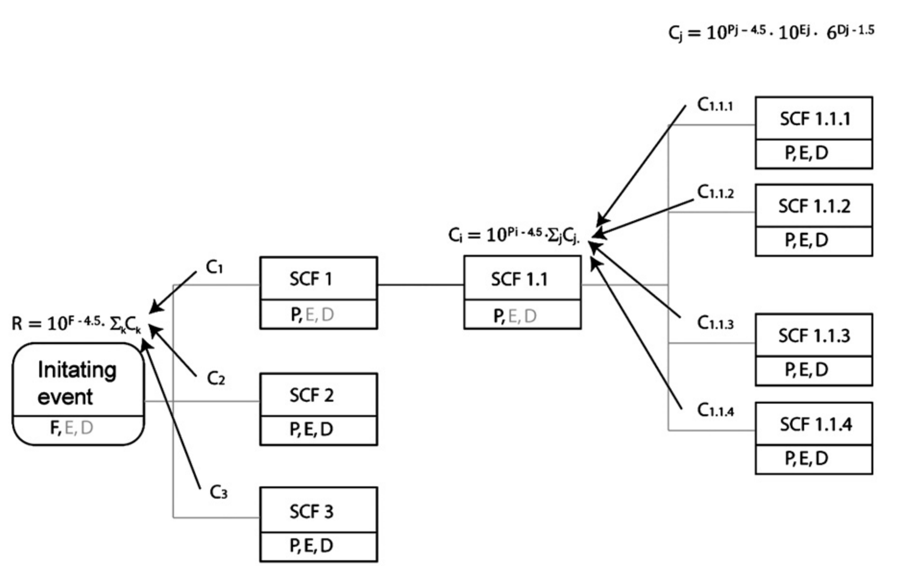

Fig. 4. Calculation procedure for cascade diagram.

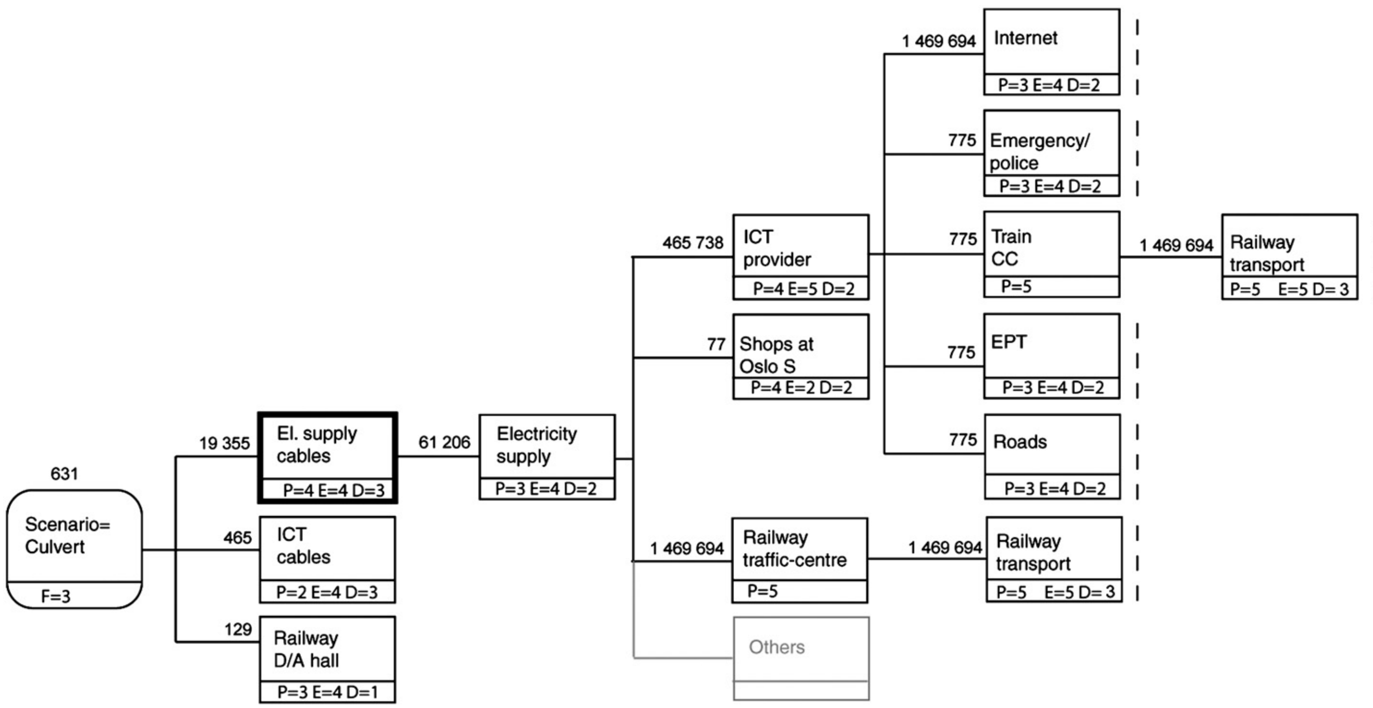

Fig. 5. Cascade diagram for culvert scenario, showing interdependencies with values for ⟨*P*, *E*, *D*⟩. Black frame indicates redundancy. EPT is Electronic Payment Transfer. Train CC is train communication.

semi-quantitative approach. In addition, fault tree analysis (FTA), event tree analysis (ETA) [24], and network models of the infrastructure and capacities can be used, either separately or in combination. An example of use of FTA for assessment of electrical power system reliability, where FTA is integrated with the power flow model, can be found in Volkanovski et al. [25]. In Ref. [26], network analysis in the form of a novel random flow propagation model is presented, which identifies weaknesses in an electrical power transmission system.

3.5. Step 5—evaluate risk and measures to reduce interdependencies

When the analysis of the site specific event/scenario is completed, the results should be evaluated with respect to the corresponding generic event. For example, can a similar event occur in other places/locations, and if yes, do these events have higher or lower risks than the specific scenario being investigated. In the culvert case this means that the total number of similar objects (culverts) in Oslo should be assessed. To get an overall picture of the risk related to this type of scenario, one should ask

- Is the culvert being analyzed worse or better than other culverts with respect to interdependencies and accident consequences?
- Is there a need for analyzing other culverts?

Finally, the cascade diagram can be used to suggest risk reducing measures, in particular by reducing interdependencies between the SCF, for example by introducing additional barriers. The effects of risk reducing measures can also be evaluated in the cascade diagram. A risk reducing measure may be to introduce redundancy of the electricity supply to the ICT provider. In Fig. 5, this means that the probability, *P*, for the ICT provider may be reduced, for example by two units (categories). By redoing the calculations, the risk related to the accident scenario is reduced by 20.8%. The risk reduction may be increased if redundancy is introduced to the electricity supply in general, for example by putting an additional cable into the culvert. Then the risk decreases by 86.7%. Usually, risk reducing measures implemented early in the chain of events have more influence on reducing the risks, than those implemented later on in the chain of events.

In general, the evaluations can include a high number of stakeholders, and they should be involved in the assessments of risk reducing measures. Often, the fields of responsibilities between private enterprises and public authorities are unclear, which can lead to challenges when implementation of different measures is discussed. The stakeholders may have various interests, for example, direct economic interests, indirect short-term and long-term interests, sector interests, societal interests, and there may be differences with respect to willingness to pay for measures and to accept risks.

3.6. Step 6—cost/benefit analysis (optional)

In some cases it may be useful to formalize the trade off process when there are huge costs associated with implementing a risk reducing measure. In the DECRIS project, a first attempt was made to develop normative guidelines for trade offs, in terms of risk matrices. The relevant risk matrices were established during review of similar studies and discussed with the EPG in Oslo. Although the content of the risk matrices was not approved to represent official trade offs for the city of Oslo, interesting results can be deduced.

To "translate" the risk matrices into some kind of *trade off equation*, the procedure is as follows:

(i) For each consequence dimension, such as safety, economy, environment, and loss of service (e.g. railway transportation), categories similar to those presented in Table 1 were established.
(ii) If it is assumed that category 1 for economy corresponds to a category 1 for loss of service, category 2 for economy corresponds to a category 2 for loss of service, and so on, the implicit trade off between economy and loss of service may be derived.

(iii) For loss of service, the consequence is further described by extent (e) and duration (d), as shown in Table 1. A first order approximation for the total consequence will be to take the product of e and d, which then represents the total person hour of loss of service.
In DECRIS, a separate matrix was established [27], where the various combinations of e and d were assessed: For example, an event resulting in one hundred to ten thousand persons losing a critical service in between one day and one week was considered as *serious*. Similarly, a *serious* economic impact was considered to be in between ten and one hundred million NOKs.

(iv) By systematically treating all consequence categories, a regression line can be fitted in order to connect economy to loss of a critical service. If y represents the economic impact (in million NOK), and $x = ed$ represents the total person hour in terms of loss of service, the following log–log equation can be established:

$$\ln y = 0.58 \ln x - 3.1 \tag{8}$$

The culvert scenario gives approximately 1.5 million person hours lack of service for the extreme event that really did happen at Oslo S. The economic impact of this is by Eq. (8)

$$y = \exp(0.58 \ln 1500000 - 3.1) \approx 170 \text{ million NOKs} \tag{9}$$

Risk reducing measures established in Step 5 may now be treated by a formal approach, keeping in mind that Eq. (8) only is a first order assessment in the trade offs.

Note that due to the non-linear relation, Eq. (8) is applied for all consequences of the product of e and d. Next, the cost figures are propagated to the left in the cascade diagram by multiplying with probabilities and adding contributions from each branch. The expected "cost" given that the scenario occurs is then found to be approximately 2.5 million NOKs, and by multiplying with the frequency of the scenario we are left with an expected yearly cost of approximately 80,000 NOKs. A redundant cable will almost eliminate the expected cost; hence such a measure may be defended if the yearly capital cost is in the order of magnitude of 80,000 or less.

In railway transportation a delay is often valued in the range of 3 NOKs per passenger minutes (averaged over various categories of travelers). A linear cost function of passenger minutes coincides with Eq. (8) for $x \approx 500{,}000$ person hours. For smaller values of x, Eq. (8) gives a higher value compared to railway transportation, and for larger values the result is turned the other way around due to the non-linearity of Eq. (8). Therefore, a proposed measure more in line with what is used in transportation would be

$$\ln y = 0.8 \ln x\text{-}7.5 \tag{10}$$

where y still is the cost equivalent in million NOKs, and x is person hours. Here 0.8 represents a damping of huge consequences, compared to Eq. (8). Note that a calibration of such a transformation usually is required, and in most cases it is necessary to differentiate depending on the type of critical infrastructure.

4. Discussion and conclusions

This paper describes a method to analyze interdependencies as part of a cross-sector RVA of critical infrastructures. A case study of Oslo (the culvert at Oslo Central Station) has been used to exemplify the approach. Analysis of interdependencies must be an integral and essential part of RVA.

With respect to the culvert event, there was redundancy of the electricity cables, but the two cables were put into the same culvert and therefore both affected by the fire. The cascading effects of the short-circuiting and the fire on the infrastructures had major consequences for the inhabitants of Oslo (and of neighboring communities). When assessing the needs for risk reducing measures, such as redundancy, the benefits to the single infrastructure owner should be considered along with benefits to other infrastructures that may be affected by the event.

Determining different stakeholders' responsibilities, interests, and contributions may be a challenging part of an interdependency analysis. The contractor, who in many cases also is the owner of the problem, has to clarify the objectives of the analysis, specify acceptance criteria, and be specific about who is responsible for implementation and follow up of risk reducing measures. Across sectors, it may be difficult to specify the responsible actors, which means that cooperation between the actors has to be organized, as well appointing the responsible person(s). One infrastructure owner may not hold the complete picture of their infrastructure. This may complicate the work on identifying and assessing consequences, and therefore the means to implement risk reducing measures may be limited. An example is loss of electricity supply—the net supply company does not have the possibility to determine all consequences for end users. Detailed analyses of the consequences have to occur at the infrastructure owners' and end users' depending on their need for electricity supply.

Another challenge is that RVA of societal risks may require use of classified information, either company-specific or nationally. Security grading limits the possibility for releasing information to the public, and there may also be a need for security clearance of the participants in the analysis. The case study provided important opportunities for exchange of knowledge and improved cooperation between stakeholders and infrastructure owners within the Emergency Preparedness Group (EPG) of Oslo.

Through the case study, the critical infrastructure owners participating in the EPG have been given strong incentives to increase their cross-sector cooperation, for example, by putting increased efforts into development of common maps of their infrastructure networks. The analyses showed that there are interdependencies between the SCFs that should be taken into account by infrastructure owners and by the Emergency Preparedness Agency, in both risk analyses and in the emergency preparedness work.

Several methods to analyze interdependencies between critical infrastructures have been proposed in recent years. However, if such methods are to be used by the stakeholders, it is important to keep it user friendly, even when addressing complex and large systems. To implement many detailed analyses, and integrate the results into a total risk analysis to be used as a basis for prioritizing risk reducing measures, might be resource demanding. Balancing between complexity and simplicity is challenging. However, it is possible to use the method suggested in the present paper to perform a rather "coarse" analysis to identify major risks and vulnerabilities. One advantage is the use of cascade diagrams, which is a logical way of structuring the interdependencies. Another advantage is the possibility of evaluating the effects of risk reducing measures by changing the input parameters in the cascade diagram.

The suggested interdependency analysis and the case study will be used as input to future research on interdependencies related to RVA. The importance of the project was emphasized in the Norwegian government's White Paper no. 22 (2007–2008) on knowledge based societal risk [28].

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