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A framework for risk criteria for critical infrastructures: fundamentals and case studies in the Netherlands

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Abstract

Critical infrastructures are complex societal systems. For that reason, risk criteria for critical infrastructures are also 'part' of the risk criteria for complex societal systems. The questions to be resolved are: (1) are the societal risk criteria of complex systems defined and quantifiable; and (2) is it known how the risk criteria of critical infrastructures relate to the risk criteria of the complex system as a whole. In other words, what certainty is there that the risk criteria of critical infrastructures meet the risk criteria of complex systems as a whole. A complex system in this respect may be a society as a whole, e.g. a nation.

KEY WORDS: risk criteria; system engineering; fundamental approach; critical infrastructures

1. Introduction

At least four approaches to the extent of risk criteria can be distinguished (see for backgrounds, Shrader-Frechette (1985)):

(1) criteria based on risk-cost-benefit measures, e.g. like in complex and expensive health services,
(2) criteria based on past performance or revealed preferences, e.g. like in major hazards licensing and rail road safety of high speed lines,

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(3) criteria based on societal or laymen's preferences, expressed preferences, e.g. like in asbestos abatement or approaches to dioxin-caused health problems, and
(4) criteria based on natural standards, e.g. like in some environmental risk criteria.

Another important feature is meeting the criteria in practice. Not in all cases are risky infrastructures monitored sufficiently in the operational phase. In many cases risk criteria apply for judging the design phase (e.g. in major hazards establishments (Institute of Chemical Engineering, 1985, Health and Safety Executve, 1989), dyke renewal or storm surge-barriers against flooding (Technical Advisory Committee on Water Retaining Structures, 1984)) or may even be more appropriate for the demolition phase (as may be expected for nuclear energy as a whole). This requires performance of qualitative assessments next to the quantitative design risk criteria. As this may not necessarily be the case in all circumstances, 'repair' strategies are warranted to meet the original design criteria, in particular, when common-cause mechanisms in safety management overrule 'as designed' management and may violate the risk criteria with orders of magnitude.

The goal of this paper will be to overview the fundamentals of risk criteria for critical infrastructures in the light of societal risk criteria and the life cycle of the systems at hand. It will also be shown how inherently difficult risk assessments of subsystems, which are part of critical infrastructures, can be fairly judged upon against the risk criteria of the critical infrastructure as a whole. The paper will also highlight the probabilistic risk criteria used in the Netherlands for several critical infrastructures: airports, railroads, air travel, road safety, and transport of hazardous materials.

2. Fundamentals of risk criteria

Risk has always been associated with probabilities (or frequencies) and consequences, often in a multiplicative form, expressing expectation values. Kaplan and Garrick (1981) associate risk with probabilities and consequences related to specifically defined accident scenarios. They express risk as a balance between hazards and safeguards. They then define the risk of a certain activity as a set of triplets

$$R = \{< s_i\,,\, p_i\,,\, x_i >\} \qquad i = 1, 2, \ldots, N$$

where R is the risk, s_i is the ith accident scenario, p_i is the probability of occurrence of the ith accident scenario and x represents the potential consequences after the ith accident scenario has been occurred.

Verbally, this means that three questions must be answered:

(1) What can happen? Or, what can go wrong?
(2) How likely is it that that will happen?
(3) If it does happen, what are the consequences?

For complex societal systems as a whole, like a nation, *individual risk* is normally used as a measure, which varies between 10^{-5} and 3×10^{-4} deaths per year for occupational, traffic and consumer risks. The individual risk is then taken over the whole population at stake and a time period of one year. Although no general individual risk criteria are set, the tendency is to measure those against the *de minimis* of 10^{-6} to 10^{-5} deaths per year (Mumpower, 1986). In some cases, like high speed train links, individual risk criteria are set in the Netherlands (Frijters *et al.*, 1998). The same is true for the zoning between hazardous chemical facilities and residential areas, at an individual risk contour of 10^{-6} deaths per year (the Dutch VROM-standard, Ministry of Housing, Land Use planning and Environment (1988)).

For critical infrastructures, however, also societal risks are defined Fischhoff, 1990; Slovic *et al.*, 1994). For social or group risks, the next step is to order the scenarios with increasing measure of potential consequences. The cumulative probabilities (or frequencies) for exceeding a certain number of deaths is then derived from the probabilities of all scenarios contributing to the exceedance of a particular number of deaths. Graphically this is represented in an FN-curve. Orientation curves are defined for the group risk of hazardous chemical facilities (the Dutch VROM-type of curves, with a decreasing quadratic function expressing lower accepted frequencies with increasing potential number of deaths).

The societal acceptable risk is judged at a national level by placing an upper-bound upon the expected number of fatalities per activity per year $E(N_{di})$. However limiting only the expected number of deaths does not account for risk aversion. As presented in Vrijling and Van Gelder (1997) and Slijkhuis et al. (1997), risk aversion can be represented mathematically by adding a confidence requirement $\sigma(N_{di})$ to the norm:

$$E(N_{di}) + k \cdot \sigma(N_{di}) < \beta_i$$

where $k = 3$; the risk aversion index and β_i a policy factor (β_i varies from 0.01 for involuntary no benefit activities to 100 for completely voluntary direct benefit activities, as introduced by Vrijling et al. (1995)). Starr (1969) also observed public tolerance of 1000 times larger risks from voluntary than from involuntary activities with the same benefit.

The synthesis of this national risk criterion and the VROM-type of local societal risk criterion approach leads to an upper-bound to the FN-curve of the local activity, which is inversely proportional to the number of independent places N_A and the square of the policy factor β_i:

$$1 - F_{N_{dij}}(x) \leq \frac{C_i}{x^2} \quad \textit{for all} \quad x \geq 10$$

where $C_i = \left[\dfrac{\beta_i \cdot 100}{k \cdot \sqrt{N_A}} \right]^2$ and $1 - F_{N_{dij}}(x) = P(N_{dij} > x)$. The numerical value of the tolerable frequency can, within certain limits, be tuned by the factor β_i. A mathematical-economic approach of the acceptable risk should be included in the philosophy of acceptable risk (as also followed in Dantzig (1956), Dantzig and Kriens (1960) and Voortman and Vrijling (2001)). It is important to weigh the reduction of risk in monetary terms against the investments needed for additional safety. In this way an economic judgement of the safety level proposed by the two other approaches is added to the information available in the decision-making process. It is advised to include in this approach an estimate for the value of a human life (present value of the nett national income per capita) to help avoid decisions that implicitly attach unrealistically high values to loss of live. Alternative approaches are achieved by willingness-to-pay approaches, in which case monetary values of human life are derived from dedicated questionnaires among people.

Economic optimization includes only economic dimensions of risk. Therefore, it is very often deemed insufficient for responsible decision making. Nathwani *et al.* (1997) proposed a compound indicator, including economic benefits and life expectancy. The general form of this so-called life quality index (*LQI*) is:

$$LQI = g^{w} \cdot e^{(1-w)}$$

where g is personal income, e is life expectancy and w is model parameter. The parameter w is derived by analysing statistics on the amount of time spent working. See Nathwani *et al.* (1997) for details. The life quality index can be combined with the aforementioned concept of economic optimization, by writing both personal income and life expectancy as a function of the probability of being killed in an accident P_{fi}. Since the decision to improve the safety of an activity has an influence over several years, account has to be taken of the capitalization of the life quality index. The cash-flow in a year where no investment is made in terms of personal income, capitalized to the year where the decision is made ($t = 0$), is given as:

$$g\left(P_{fi}, t\right) = \frac{\left(N \cdot g_0 + \left(1 - P_{fi}\right) B_0 - P_{fi} \cdot S\right) \cdot \left(1 + r_e\right)^t}{N \cdot \left(1 + r_p\right)^t \cdot \left(1 + r - i\right)^t}$$

where N is population at the beginning of the plan period, B_0 is yearly turn-over when no accident occurs, r_p is growth rate of population, g_0 is personal income at time $t = 0$ and r_e is rate of economic growth.

The life expectancy can be derived as a function of the probability of being killed in an accident by considering death statistics of society. The lifetime distribution of the population can be found by analogy to time-dependent failure of components, according to:

$$F_{\underline{T}}\left(t\right) = 1 - e^{-\int_0^t r(\tau)\mathrm{d}\tau}$$

where $r(t)$ denote the age-dependent death rate. The overall death rate in the Netherlands follows by the ratio of the total number of deaths in a year (135 000) and the total population (16 million), giving $r = 8.7 \cdot 10^{-3}$ per year. People of the ages 6–20 have a probability of decease of $1.0 \cdot 10^{-4}$ in a year. This analysis takes all possible causes of death into consideration and no distinction is made between activities.

The life expectancy at birth is found simply by integration of the lifetime probability density function:

$$e_0 = \int_{t=0}^{\infty} t \cdot f_{\underline{T}}\left(t\right) \mathrm{d}t$$

The life expectancy under the risk of a certain activity can be calculated by replacing the age-dependent death-rate $r(t)$ by:

Table 1. Decrease in the life span due to extra probability of dying

Extra probability of decease in a year	*Expected age*	*Decrease of the life span in years*	*Decrease of expected life in days*
10^{-3}	74.97	3.16	1153
10^{-4}	77.81	0.32	117
10^{-5}	78.10	0.03	11
10^{-6}	78.13	0.00	1
10^{-7}	78.13	0.00	0

$$r(t) = r_0(t) + P_{fi} \cdot P_{d|fi}$$

where $r_0(t)$ denotes the age-dependent death rate without considerations of the activity's risk.

Note that the above expression implicitly assumes that the added death probability is age-independent. Table 1 presents some results of the decrease in life span under additional risks (10^{-7} to 10^{-3} per year). According to the Dutch Central Bureau of Statistics, the life expectancy in the Netherlands is 78.13 years.

Assume that C is the total cost of reducing the risk in order to meet a target safety requirement. The population that bears the total cost for a national standard to be applied universally is taken as the total population (1.6×10^7 for the Netherlands). The cost of the regulation per capita is therefore $-C/1.6 \times 10^7$. The real gross domestic product per person per year in the Netherlands is approximately Euro 20 000. The proportion of time, w, spent in economic activities to create wealth $w = 12.5\%$ and $K = (1 - w)/w = 7$. The ratio $-C/(1.6 \times 10^7 \times 7 \times 20\,000) = C \cdot 4.5 \times 10^{-13}$ represents the economic impact expressed in terms of relative loss of life expectancy.

A decrease in the death rate, dM, caused by the regulation should be estimated. It is given by the ratio of the number of lives saved by the regulation and the total population. The net benefit-gain in life expectancy follows from 19.2 dM (according to Nathwani *et al.*, 1997).

Finally, a decision criterion to accept or reject a live-saving regulation depends on the ratio 19.2 $\mathrm{d}M/C$ $4.5 \times 10^{-13} = 4.3 \times 10^{13}$ $\mathrm{d}M/C$. If, because of a regulation measure, L lives per year can be saved, then $\mathrm{d}M = L/1.6 \times 10^7$. So the ratio can be rewritten as 2.7×10^6 L/C. In other words: if $2.7 \times 10^6 L < C$, the regulation should be rejected and otherwise accepted. The lifetime personal income and the lifetime life expectancy are combined by using the definition of the life quality index. This model can be succesfully used to support decisionmaking concerning acceptable risk issues as shown in Voortman *et al.* (2001).

In assessing the required safety of a system the approaches described above should all be investigated and presented. The most stringent of the criteria should be adopted as a basis for the 'technical' advice to the political decision process. However all information of the risk assessment should be available in the political process.

Finally, it should be realized that the philosophy and the techniques set out above are just means to reach a goal. The goal *managed safety* should not be lost sight of, when dealing with the tools, that are provided as instruments to measure an aspect of the entire situation.

So after the construction of the technical system and the start of the activity, a control-system should be put in place to observe the failure frequencies and the consequences as far as possible.

3. Practical situations

To gain experience and to test the proposed framework on practical situations, especially the group risk criterion, the framework was applied to a number of activities. The activities comprise, the extension of the national airport Schiphol, air travel, the transport of dangerous chemicals over water, and the car traffic. Not all activities comply with the risk criteria. The testing leads in the case of the group risk for line sources like canals and pipelines to a small redefinition.

3.1. EXAMPLE 1: AIRPORTS

At Schiphol airport, surrounded by inhabited areas, 90 000 planes leave and arrive every year bringing the total number of movements to 180 000 per year. As the probability of an accident, averaging historical data, is estimated at 5.0×10^{-7} per movement (NLR, 1993), then the probability of a crash at Schiphol is $180\,000 \times 5.0 \times 10^{-7} = 0.09$ per year. The number of fatalities at the ground (excluding passengers and crew) in the case of a crash is estimated at 50, when in a first approximation every crash is assumed to hit inhabited areas.

According to the VROM-rule (with $C_i = 10^{-3}$ corresponding to a probability of 10^{-5} for the $5.0\times10^{-7} > \frac{10^{-3}}{N_{di}^2} = \frac{10^{-3}}{50^2} = 4.0\times10^{-7}$ death of 10 people in a year) for societal risk one single flight movement (per year) would already be unacceptable because as might be expected from the large number of aircraft movements the expected value and the standard deviation of the total number of fatalities in a year are considerable:

$$E(N_{di}) = N_{A_i} \times p_{fi} \times N_{dij|f} = 180\ 000 \times 5.0 \times 10^{-7} \times 50 = 4.5$$

$$\sigma(N_{di}) \approx \sqrt{N_{A_i} \times p_{fi}} \times N_{dij|f} = \sqrt{180\ 000 \times 5.0 \times 10^{-7}} \times 50 = 15$$

A dramatical improvement of aircraft safety would be required if the total airport operations were to meet the VROM-rule. If the risk of Schiphol is judged on a national level as seems appropriate for a national airport, the result is $E(N_{di}) + k \times \sigma(N_{di}) = 49.5 \leq \beta_i \times 100$. A value of the policy factor $\beta_i = 0.5$ should be chosen, in order to fulfill the above inequality, which means that the situation depicted here will not be acceptable without discussion.

Refined computer calculations (NLR) show a more acceptable picture than the crude computations presented above. However the 10^{-5} and the 10^{-6} individual risk contours are respectively just and far outside the perimeter of Schiphol. This is unacceptable according to the VROM-rule for individual risk, but using the framework developed here the situation might be acceptable if $\beta_i = 0.1$ for a national airport used by a considerable part of the citizens. The FN-curve calculated in NLR is also more favourable than the crude approximation presented above, but unacceptable by several orders of magnitude when compared with the VROM-rule for societal risk (Fig. 1). If the new set of

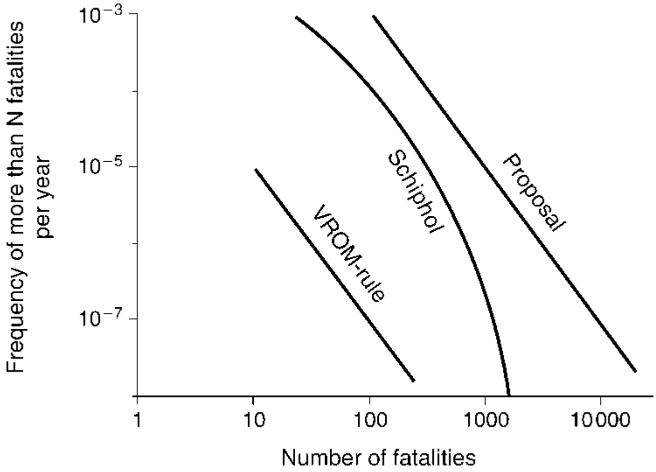

Fig. 1. FN-curve for Schiphol, in relation to the VROM-criterion, and the new proposed criterion.

rules is applied and C_i is adapted to 11, because $N_{Ai} = 1$ for one national airport and $\beta_i = 0.1$ (in other words if the judgement is placed at a national level and the benefits are taken into account), the FN-curve is acceptable as Fig. 1 shows.

The benefits of the airport have to be weighed against the external risk and the possibilities of improvement have to be studied, before a political decision to increase β_i from 0.01 to 0.1 can be taken. Additionally a decision has to be made that Schiphol will be the only major airport in Holland. Implicitly the Dutch government has taken both decisions, when it proposed to accept the individual as well as the societal risk connected to the extended Schiphol.

3.2. EXAMPLE 2: AIR TRAVEL

It is interesting to study the safety of air travel besides the safety of the airport because this regards passengers instead of third parties. The individual risk equals approximately 5×10^{-7} per flight (take-off and landing), if it is assumed that half of the passengers die in a crash. The individual risk depends on the number of flight that the individual makes in a year. With 10 flights the individual risk becomes 10^{-5} and with 100 flights 10^{-4} per year. The former is according to the rule for acceptable individual risk acceptable, the second will only be endured on a voluntary basis ($\beta_i = 1$) or in case of a direct benefit (pilot).

The societal risk level of the air traffic approaching and leaving the airport can be calculated if the simplifying assumption is made, that say half of the passengers (i.e. approximately 200) will die in a crash. The expected value and the standard deviation can be found by:

$$E(N_{di}) = N_{A_i} \times p_{fi} \times N_{dij|f} = 180\ 000 \times 5.0 \times 10^{-7} \times 200 = 18$$

$$\sigma(N_{di}) \approx \sqrt{N_{A_i} \times p_{fi}} \times N_{dij|f} = \sqrt{180\ 000 \times 5.0 \times 10^{-7}} \times 200 = 60$$

The national criterion indicates $E(N_{di}) + k \cdot \sigma(N_{di}) = 198 \leq \beta_i \times 100$ that the societal risk would be acceptable, if $\beta_i = 2$ describes the attitude of the society towards air travel. It seems likely that the situation sketched here will require a national debate to decide if improvements have to be made, as $\beta_i = 0.1 - 1$ reflects the public attitude better.

3.3. EXAMPLE 3: ROAD SAFETY

The car traffic forms an interesting example to test the theory, because the number of independent installations $N_A = 4 \times 10^6$ is very large and the victims are passengers/users. If the number of people in the car is assumed at two and the probability to die in a crash at $p_{d|f} = 0.1$ (1200 deaths in 12 000 heavy accidents per year), then the conditional expectation and the standard deviation of the number of deaths per car are equal to 0.2 and 0.42 respectively. Using the mentioned general formulae the expected value and the standard deviation at national level are calculated with:

$$E(N_{di}) = N_{Ai} \times p_{fij} \times E(N_{dij|f})$$

$$\sigma(N_{di}) = \sqrt{N_{Ai} \times p_{fij} \times (1 - p_{fij}) \times E(N_{dij|f})^2 + \sigma(N_{d|f})^2}$$

Substitution of these expressions in the national norm equation gives an expression with p_{fij} as unknown. If $\beta = 1.0$ is adopted the acceptable probability of a car accident is 0.9×10^{-4} per year per individual. The expected total number of casualties amounts to 72 per year with a standard deviation of 8.8. A choice of $\beta_i = 10$ leads to an increase of the acceptable probability of an accident to 1.1×10^{-3} per car per year. The expected total number of casualties amounts to 972 per year with a standard deviation of 30.8. This is more in line with the actual situation, where the traffic claims approximately 1200 lives per year.

Here a contradiction arises between the acceptable individual and the societal risk. The $\beta = 1$ value that follows from the individual viewpoint with respect to car traffic would ask for a considerable reduction of the actual societal risk of 1200 to an acceptable level of approximately 72 deaths per year. However observing the efforts of Dutch NGO Safe Traffic it could be argued that the public finds the societal risk too high and strives for a reduction.

3.4. EXAMPLE 4: TRANSPORT OF DANGEROUS SUBSTANCES

The transport of dangerous goods over water, road and rail should comply with the safety norms. To prevent hasty and incorrect decisions the Dutch Ministry of Transport decided to start with an inventory of existing risks along waterways before proposing a norm. The calculated FN-curves for the passages of cities and villages appeared to exceed the VROM-norm by far. Arguing that the norm was developed for point sources like plants and not for line sources as a waterway, the norm was rather arbitrarily applied to every single km of waterway.

A better approach defines the city or village as the entity that needs protection and calculates the FN-curve per settlement. Applying the framework with choices of $\beta_i = 0.1$ and $N_{Ai} = 100$ settlements along Dutch waterways the value of $C_i = 0.11$ results. In Fig. 2 the lines for $C_i = 10^{-5}$, 10^{-3} and 10^{-1} are drawn. Apart from Flushing, all villages comply approximately with the norm. It is a political decision, if $\beta_i = 0.1$ expresses the societal preferences adequately.

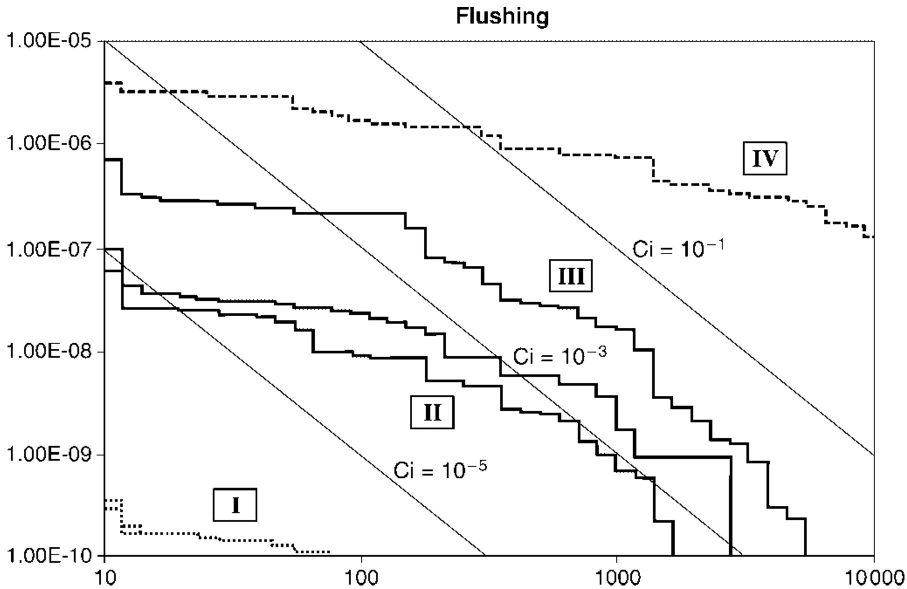

Fig. 2. The FN-curves for the transport of dangerous substances over the Western Scheldt.

3.5. EXAMPLE 5: HIGH SPEED TRAIN

The high speed train section between Amsterdam and Antwerp is meant to improve the environment by substituting car and air travel with a more energy efficient rail link. In addition to this the management has set the goal to provide a mode of transport that improves the safety in comparison with the substituded modes. A safety plan is being made, that includes a safety philosophy with risk criteria formulated along the lines explained above.

Several groups can be distinguished, each of them having their own specific involvement with the HST, characterized by the degree of voluntariness and individual cost/benefit assessment (passenger, staff, resident, passer-by). For each of these groups an individual and a societal acceptable level of risk is tentatively determined. The acceptable risk levels are based on a comparison with historical accident rates and the national criterion. In the Tables 2–4 the comparison of the societal risk is made between the multimode situation and the situation where the HST is functioning.

Society will perceive the safety of the HST in terms of the total yearly number of accidents casu quo casualties. The basic measure for individual risk perception is the

Table 2. Present situation

Mode	$E(N_{di})$	$\sigma(N_{di})$	$E(N_{di}) + k\sigma(N_{di})$
Car	7.1	2.7	15
Airplane	0.3	4.1	13
Train	0.05	0.4	1.3
Total	7.5	4.9	22

Table 3. Future situation with old traffic substituted and new traffic generated by HST

Mode	$E(N_{di})$	$\sigma(N_{di})$	$E(N_{di}) + k\sigma(N_{di})$
HST substituted	0.03	0.4	1.3
HST generated	0.02	0.25	0.8
Total	0.05	0.5	1.5

Table 4. Proposed risk criteria for the Dutch HST-South

Object	*Individual risk*	*Societal risk*	
	$p_{fi} \cdot p_{d\|f}$	$E(N_{di})$	$E(N_{di}) + k\sigma(N_{di})$
Passenger	2×10^{-6}	0.15	2.0
Train personnel	2×10^{-5}	–	–
Rescue personnel	ALARA	–	–
Third party	1×10^{-6}	–	–
Suicides (train)	–	10	10 ($k = 0$)

risk per trip or the risk per passenger kilometre, which measures can be translated to the probability of dying per year for the ‘average’ passenger. After the acceptable risk levels for each group have been finally set, the design of the HST transportation system has to fulfil these safety requirements. Using decomposition of the system, an optimization of the distribution of the occurring risk over the several subsystems including the management, with respect to costs, is pursued.

4. Summary

In this paper the fundamentals of a framework for risk criteria for critical infrastructures are presented. The framework is applied to five Dutch case studies.

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