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The safety of risk or the risk of safety?

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ABSTRACT: Safety is nowadays one of the main items on the agenda during the planning, realisation and management of most large-scale projects, particularly in infrastructure and building projects in intensively used areas such as multiple use of land projects. It is vital that safety aspects are properly assessed at an early possible stage of the project. In this paper relations between safety and risk are suggested. In order to quantify the safety in objective terms, risk (analysis) is used as an important tool. However, definitions of risk vary from global and informal to objective variants and consists both psychological and mathematical elements. When a risk analysis is performed, one has to consider these definitions. In this paper, both psychological and mathematical risk definitions are mentioned and their interrelation is described. An essential element in risk assessment is risk evaluation. When a risk analysis is performed, it is also important to realise that decision making about risks is very complex and that not only technical aspects but also economical, environmental, comfort related, political, psychological and societal acceptance play an important role. Finally, a recommendation has been made for narrowing the gap between deterministic and probabilistic approach by use of Bayesian Networks. It appears that these networks are also useful in order to integrate psychological and mathematical definitions of risk.

1 INTRODUCTION

From a psychological, social and risk point of view, safety is a wide notion. According to [Vrouwenvelder et al., 2001], safety is the state of being adequately protected against hurt or injury, freedom from serious danger or hazard. In the philosophy of safety, safety is usually classified into *social safety* and *physical safety* [Durmisevic, 2002; Suddle, 2002^{A}; Voordt & Wegen, 1990]. Social safety implicates the behaviour among persons. Crime incentive factors, spatial factors, institutional factors and social factors of an area are characteristics of social safety. In contrast, physical safety contains both the probability of a person being killed or injured by *natural hazards*, like bad weather, an earthquake, floods and the probability by *man-made hazards* like traffic, calamities by transport of dangerous materials, calamities by nuclear reactors etc. In some cases, like fire, it is difficult to classify which kind of safety it is. A subdivision within physical safety is made by *internal safety* and *external safety* [Vrijling et al., 1998]. The following subdivision, here ranked according to increasing benefit to the persons at risk is frequently found.

Safety		
Social Safety	*Physical Safety*	
Crime incentive factors Spatial factors Institutional factors Social factors	*Natural & Man-made hazards*	
	Internal Users Passengers Personnel	External Third parties

Figure 1. Subdivision of safety.

2 SAFETY AND RISK

2.1 *Introduction*

Generally, safety consists both of subjectivity and objectivity elements. A person who experiences that he is safe from a psychological point of view, does not automatically implies he is safe from a mathematical point of view and vice versa. The relation between subjectivity and objectivity components of safety can be presented with aspects of irrational behaviour [Bouma, 1982].

	Subjective Safe	Subjective Unsafe
Objective Safe	*Healthy unconcern*	*Paranoia*
Objective Unsafe	*Naivety*	*Healthy anxiety*

Figure 2. Aspects of irrational behaviours.

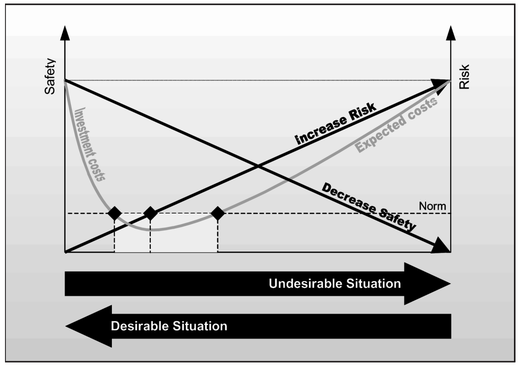

Figure 3. Model safety vs risk [Suddle, 2002A].

Subjective safety is related to psychological aspects (see also [Stoessel, 2001]), while objective safety is based on mathematical grounds. Note that sometimes the objective safety is also based on subjective estimates. To define and to quantify the objective elements of safety, it is vital to link safety with *risk*. In essence, it can be assumed that safety, either internal or external, is complementary with the level of risk [Suddle, 2002A] (see fig. 3). This means to reach a low-risk level, one has to make investments for safety measures, while one may expect both human and financial risks, such as casualties and loss of human live in accordance with a minimum level of safety (high-risk level). If the level of acceptability and tolerability of risk would be embedded correctly, the optimum level of safety would have laid on the minimum of the sum of investments and expecting risks.

The survey of Vlek [Vlek, 1990] yielded 20 definitions of risk, which vary from global informal definitions to objective variants. The 11 formal definitions of risk or riskiness, which can be distinguished from those 20, are presented in table 1.

Table 1. Formal definitions of risk or riskiness (adapted from [Vlek, 1990]).

1. Probability of undesired consequence.
2. Seriousness of (maximum) possible undesired consequence.
3. Multi-attribute weighted sum of components of possible undesired consequence.
4. Probability x seriousness of undesired consequence (“expected loss”).
5. Probability-weighted sum of all possible undesired consequences (“average expected loss”).
6. Fitted function through graph of points relating probability to extent of undesired consequences.
7. Semivariance of possible undesired consequences about their average.
8. Variance of all possible undesired consequences about mean consequences.
9. Weighted sum of expected value and variance of all possible consequences.
10. Weighted combination of various parameters of the probability distribution of all possible consequences (encompasses 8 en 9).
11. Weight of possible undesired consequences (“loss”) relative to comparable possible desired consequences (“gain”).

This collection of risk definitions may be considered by viewing risk as the characterization of: (a) a single possibility of accident, loss or disease (defs 1–4), (b) a collection of accident possibilities (defs 5–7), and (c) an *activity* having accident (and other) possibilities (defs 8–11) [Vlek, 1996]. Table 1 does hardly consist informal definitions of risk, which are related to social and psychological aspects. Still, the community demands that engineers and designers take both social and psychological aspects into account when doing and evaluating risk analysis.

2.2 *Psychological definitions of risk*

One of the first conceptual analyses of risk is carried out by Vlek [Vlek, 1990]. This analysis is based on decision-making and empirical-psychological work on the nature and the dimensions of risks and hazards. Examples of psychological (informal) definitions from [Vlek, 1990; Schaalsma et al., 1990] are “lack of perceived controllability”, “set of possible negative consequences” and “fear of loss”. From [Vlek, 1990], it can be concluded that one has to consider the way people interpret risk in risk management, also called *risk perception*. The interpretation is different for a single person and a group of persons [Gezondheidsraad, 1995; 1996]. The perception of risk differs by factors in relation with [Vlek, 1990]:

- The origin of the hazard
- The social context
- The personal remarks

Table 2. Basic dimensions underlying perceived riskiness (adapted from [Vlek, 1996]).

1. Potential degree of harm or fatality.
2. Physical extent of damage (area effected).
3. Social extent of damage (number of people involved).
4. Time distribution of damage (immediate and/or delayed effects).
5. Probability of undesired consequence.
6. Controllability (by self or trusted expert) of undesired consequences.
7. Experience with, familiarity, imaginability of consequences.
8. Voluntariness of exposure (freedom of choice).
9. Clarity, importance of expected benefits.
10. Social distribution of risks and benefits.
11. Harmful intentionality.

It may be assumed that these aspects are related to the risk perception and aspects of subjective safety, as presented in figure 2. According to [Vlek, 1996] dimensions of underlying perceived riskiness, which are related to risk perception, must be taken into account in risk management, as presented in table 2.

Note that these dimensions of underlying perceived riskiness consists mainly variants of both subjectivity and objectivity (as presented in figure 1). In [Vlek, 1996] different scale-levels of risk and risk management are suggested, which amplify the aspects of subjectivity. These psychological definitions, however, are basic ingredients for the assessment of risk. Besides, these add value to the perception of risk and play a vital role in risk acceptance and decision-making. Additionally, in [Vlek, 1990], it is recommended to take additional measures for the comfort of safety, especially for persons who feel themselves as unsafe, while objectively it is safe. Moreover, it is recommended in the survey [Vlek, 1990] not only to comply with the risk acceptance criteria, but also to apply the safest option regarding measures in accordance with the budget of the project. Therefore in some conditions one may deliberate the costs and the benefits of that project.

Thus, according to [Vlek, 1990; 1996] it may be concluded that (safety) measures are desired, and must be explored in the risk management process to increase the subjective level of safety. However, these argumentation are psychological and do not provide the answer to the question "how much safe or unsafe is an activity or what is the effect of a safety measure in accordance with safety and financial aspects". In order to answer such question in objective terms and to determine safety, there is a need for a quantifiable (mathematical) approach and not an informal psychological. Besides, a mathematical approach enables to compare risk of different activities and use the risk analysis as a basis for rational decision-making. It is therefore useful to quantify the aspects of subjectivity of table 2 and to integrate in decision-making.

2.3 *Mathematical definitions of risk*

The common definition of risk (associated with a hazard) is a combination of the probability that hazard will occur and the (usually negative) consequences of that hazard [Vrouwenvelder et al., 2001; Vrijling et al., 1998]. In essence, it comes down to the following expression, which is the same definition as definition 4 of table 1:

$$R = P_f \cdot C_f \tag{1}$$

where:
R = Risk [fatalities or money year^{-1}];
P_f = Probability of failure [year^{-1}];
C_f = Consequence of the unwanted event [fatalities or money].

This definition mostly is used in risk analysis. Consequences (C_f) to be taken into account include:

- Injury, or loss of life, due to structural collapse
- Reconstruction costs
- Loss of economic activity
- Environmental losses

Mostly, there is a (reverse) relation between the probability that a hazard will occur and the consequences of that hazard. More complicating still is the gradual unfolding of a host of differing definitions of risk [Coombs, 1972; Libby & Fishburn, 1977; Vlek & Stallen, 1980]. According to [Kaplan & Garrick, 1981], risk consists of three components:

- Scenario
- Probability of scenario
- Consequence of scenario

Following [Kaplan & Garrick, 1981] risk cannot be properly expressed in terms of a single number or even a single curve. In their view the best formal definition of risk is a probability distribution of possible (future) frequencies of harmful consequences, which themselves may be multidimensional in nature.

2.4 *Comparison of psychological and mathematical definitions*

The description of risk given by [Kaplan & Garrick, 1981] hardly differs from the mathematical one of [Vrijling & Vrouwenvelder, 1997], because both probability and consequence of scenario are included. According to [Kaplan & Garrick, 1981] one has to consider all hazards in account, which can be accomplished by summing up all possible hazards (scenarios) with their consequences for an activity. Therefore as an obvious extension, multiple scenarios (indexed i) may be taken into account. This can be presented in the following formula:

$$R = \sum_{i=1} P_{f_i} \cdot C_{f_i} \tag{2}$$

According to [Vrouwenvelder et al., 2001] probability is, generally speaking, the likelihood or degree of certainty of a particular event occurring during a specified period of time. Assuming that a system may be found in mutually exclusive situations H_i, and the failure F of the system (e.g. of the structure or its element) given a particular situation H_i occurs with the conditional probability $P(F \mid H_i)$, then the total probability of failure P_f is given by the law of total probability as:

$$P_f = \sum_{i=1} P(H_i) P(F \mid H_i) \tag{3}$$

Substitution of formula (3) in (2) gives:

$$R = \sum_{i=1} P(H_i) P(F \mid H_i) P(C \mid H_i \cap F) \tag{4}$$

where:
$P(C \mid H_i \cap F)$ = the probability of a consequence given that H_i and F occur.

Formulas (1), (2) and (4) are presented as mathematical variants. However, these are also mentioned in the psychological dimensions of risk (see table 1). The three components of formula (4) correspond with the definitions of risk as mentioned in tables 1 and 2. Therefore, from an objective safety assessment point of view one may assume that even psychological definitions from [Vlek, 1990] are integrated into mathematical definitions of [Kaplan & Garrick, 1981] combined with [Vrijling & Vrouwenvelder, 1997]. The psychological part of the mathematical definition emphasises particular the consequence of a scenario. From a mathematical point of view, all possible consequences are taken into account in risk analysis (see formulas (2) and (4)). Besides, the subjective aspects with accordance with psychology, which are mostly related to the acceptability of risk, are also integrated in acceptability and tolerability of risk in terms of vulnerability and the direct benefit of a person. From a mathematical point of view, the acceptability and tolerability of societal risk provides a tool in which it is common to accept less the probability of an event consisting big numbers of fatalities. This concept of risk aversion is also included in these risk acceptance criteria (e.g. societal and individual risk (see paper Suddle, S.I., *A Logarithmic approach for Individual risk: The safety-index*, this proceedings).

In some cases, especially scenarios with great consequences, *weighing factors* for all risk dimensions are used in order to make them comparable to each other and to relate them to the measures that must be taken for possible risk reduction [Coombs, 1972; Libby & Fishburn, 1977; Vlek & Stallen, 1980; Vlek, 1990; Vrouwenvelder et al., 2001]. It is, therefore, recommendable to compare and to integrate these definitions in one-dimensional weighted risk (R_w) in terms of money as following:

$$R_w = \sum_{j=1} \alpha_j \sum_{i=1} P_{f_{ij}} \cdot C_{f_{ij}} \tag{5}$$

$$R_w = \sum_{j=1} \alpha_j \sum_{i=1} R_{ij} \tag{6}$$

where:
R_w = weighted risk [year^{-1}];
α_j = (monetary) value per considered loss [].

It has to be noted that weighted risk (R_w) may consist of cost unities, which can be financial, but it is not necessary (see [Seiler, 2000]). Formulas (5) and (6) can be specified into particular risk components:

$$R_w = \alpha_1 \sum_{i=1} R_{human,i} + \alpha_2 \sum_{j=1} R_{enonomic,j} + \alpha_3 \sum_{k=1} R_{environment,k} + \alpha_4 \sum_{l=1} R_{quality,l} + \ldots \tag{7}$$

where:
α_1 = (monetary) value per casualty or injury [–];
α_2 = (monetary) value per environmental risk [–];
α_3 = (monetary) value per economical risk [–] (mostly $\alpha_3 = 1$);
α_4 = (monetary) value per quality risk [–], and so on.

According to [Lind, 1996] safety criterions are not absolute. Cost-utility is only a part of the economic, social, cultural and political assessments that are required for responsible decision-making. Note that some α_j may also be negative (e.g. time). Besides, the α_j is in particular correlated with the consequences (C_f), in which the correlation is not necessary to be linear. (The first component (human risk) of formulas (7) can be subdivided into:

$$\alpha_1 \sum_{i=1} R_{human,i} = \sum_{k=1} \alpha_{1k} \sum_{n=1} R_{human,nk} \tag{8}$$

where:
α_{1k} = monetary value per considered basic dimensions of underlying perceived riskiness as presented in table 2 [money].

So, $\alpha_{1k} \in \{\alpha_1, \alpha_2, \ldots, \alpha_{11}\}$ of table 2. These monetary values α_1, α_2, …, α_{11} are functions of subjective aspects of table 2 and can be determined by multi criteria analysis. If one adds monetary value to these different aspects, one can integrate all kind of subjective aspects into risk analysis, such as value for area effected (α_2), value for number of people involved (α_3), value for time (α_4), value for voluntariness (α_3, α_8, α_{11}), etc. According to [Seiler, 2000], the monetary value per casualty or costs per live saved of a person depends on the voluntariness of an activity (see table 3).

If these subjective aspects are quantified in weighted risk (analysis), and thus in one (monetary) dimension, safety measures can be balanced and optimised in respect of decision-making as following:

$$\text{Minimize: } C_{tot} = C_0(y) + \sum_{j=1} \frac{R_{wj}}{(1+r)^j} \tag{9}$$

where:
C_{tot} = total costs;
$C_0(y)$ = the investment in a safety measure;
y = decision parameter;
j = the number of the year;
r = real rate of interest;

Hence, one may assume that for rational decision-making it is desired to objectify the safety in terms of probability and the consequences of all events. Therefore, both mathematical and psychological approaches of risk can and should be quantified by the mathematical variant. It may also be recommended that, for safety studies and risk analysis, risk can commonly be estimated by the mathematical expectation of the consequences of an undesired event that often leads to *the sum of the product probability x consequences combined with the monetary value per considered loss*, is an interesting approach (formula (8) and (9)).

2.5 *Risk evaluation*

When a risk analysis is performed, it is also important to realize that decision making about risks is very complex and that not only technical aspects but also political, psychological and societal processes (all) play an important role [Suddle, 2002[A]; Jonkman et al., 2002]. If a risk analysis is carried out for only the qualitative part, the psychological and political aspects play a major role in risk acceptance and decision-making. Contrarily, when risk analysis is carried out till the quantitative part, limits for risk acceptance and economical criteria are considered for decision-making. Additionally, regarding safety management and control, one has to take measures regarding safety for persons who feel themselves as unsafe, while objective it is safe. This is exactly [Vlek, 1990] argued for the comfort of safety for all kind of people.

Table 3. Costs per live saved of a person depends on the voluntariness of an activity.

Voluntariness of an activity	Individual risk [year^{-1}]	Costs per life saved €
1. Voluntary risk	10^{-3}	1.500.000
2. High degree of self-determination, direct individual benefit (car driving)	10^{-4}	6.000.000
3. Low degree of self-determination, individual benefit (working conditions)	$5 \cdot 10^{-5}$	15.000.000
4. Involuntary, imposed risk exposition, no direct benefit (local resistance of dangerous installation)	10^{-5}	20.000.000

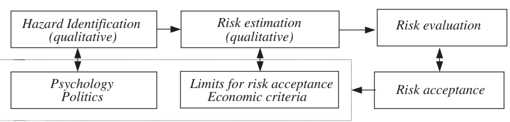

Figure 4. Risk analysis and risk acceptance [Suddle, 2002].

3 APPROACHES FOR RISK ASSESSMENT

3.1 *Deterministic and probabilistic approach*

During the 1950s and 1960s two approaches emerged for analysing safety aspects of potentially hazardous systems, including a *deterministic* approach and a *probabilistic* approach [Weaver, 1980]. The most significant difference between the two approaches is the way probability is dealt with [Vrijling and Stoop, 1999]. *Deterministic* safety analysis is focused on the causal processes of accident scenarios equals 1.

Whereas *probabilistic* risk analysis takes into account the possibility and the likelihood of uncertainty that accident scenarios might occur. As a result, in deterministic analysis the focus is on developing insights into accident scenarios and consequences, whereas in probabilistic risk analysis main efforts are made on the behalf of the quantification of probabilities [Hale, 2000; Rosmuller, 2001]. Thus, one may assume there is an existing gap between the *probabilistic* and *deterministic* methods in risk analysis. If a risk analysis is performed with present models such as fault trees and event trees, this gap will not be narrowed because of large dimensions and big complexity of such models. Nevertheless, the following paragraphs is an introduction to the theory, which shows that the existing gap can be narrowed by use of Bayesian Networks in risk analysis (see [Suddle, 2001[A]].

3.2 *Use of Bayesian Networks*

A Bayesian Network is a graphical tool that represents the relations between a set of variables and a set of directed edges between variables [Hansen, 1999; Jensen, 1996; 2001], which can be divided into events and consequences. The major advantage of Bayesian Networks is that these networks can replace and compact both traditional fault trees and event trees in one model [Bobbio et al., 2001]. Thus, these networks provide an effective tool, particularly for enormous risk analysis. According to [Friis-Hansen, 2000] the potential of Bayesian Networks are an intuitive modelling tool, partly based on artificial intelligence that adds transparency and consistency to the models. Normally, the relation between fault trees and event trees are represented in the Bowtie model, which will expand exponentially in case of the relations between the events will increases [Ale, 2002; Oh, 2001]. This can now be replaced into a single compatible Bayesian Network, which grows linear (figure 5).

A Bayesian Network consists of a set of nodes and a set of directed arrows. Each node represents a probability distribution, which may in principle be continuous or discrete. Arcs indicate conditional probabilistic dependence so that the probability of a dependent variable being in a particular state is given for each combination of the states of the receding variables. The dependence structure is thus represented by a set of conditional probability distributions. A variable, which is dependent on other variables, is often referred to as a *child node*.

Likewise, directly preceding variables are called *parents*. Nodes, which have no parents, are *called root* nodes and nodes without children are *leaf nodes*. Bayesian Networks are sometimes referred to as directed acyclic graphs (DAGs), indicating that loops (or cycles) are not allowed. A Bayesian Network is a representation of the joint probability distribution of the entire variable domain $U = \{X_1, X_2, \ldots, X_n\}$.This is seen by applying the chain rule to factorisation of the joint distribution into a chain of conditional probability distributions [Friis-Hansen, 2000]:

$$P(U) = P(X_1, X_2, \ldots, X_n) \quad (10)$$

$$= P(X_1 \mid X_2, \ldots, X_n) P(X_2 \mid X_3, \ldots, X_n) \cdots P(X_n) \quad (11)$$

$$= \prod_i P(X_i \mid pa(X_i)) \quad (12)$$

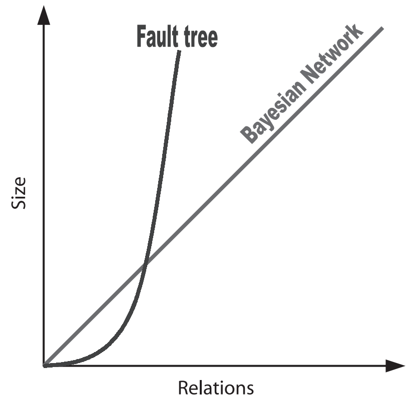

Figure 5. The size of a Bayesian Network is smaller than the traditional fault trees. Hence, a Bayesian Network is much compacter.

where $P(X_1, \ldots, X_n)$ is the joint distribution of X_1 to X_n and $P(X_1 \mid X_2, \ldots, X_n)$ is the conditional distribution of X_1 given $X_2, \ldots, X_n$. The notation $pa(X_i)$ means the set of parent variables of the variable X_i. From the updated joint table the marginal distributions of each individual variable may be found by summation over all other variables. This is desired for calculating risk for all scenarios. This is known as sum-marginalisation:

$$P(X_i) = \sum_{U \setminus \{X_i\}} P(U) = \sum_{U \setminus \{X_i\}} \prod_i P(X_i \mid pa(X_i)) \quad (13)$$

So, if the undesired events (H_i), failure modes (F), consequences (C), safety measures (M) and risk (R) are elements of the entire variable domain $U = \{X_1, X_2, \ldots, X_n\}$, than every risk analysis with Bayesian Networks is possible.

$$H_i, F, M, C, S, R \in \{X_1, X_2, \ldots, X_n\} \quad (14)$$

These safety measures may include the rescue availability or functional design, which are characteristic for deterministic risk analysis. These measures may also consist structural measures, which are characteristic for probabilistic risk analysis. Besides, integration of these measures is a vital issue from the psychological point of view, as mentioned in section 2.3. This concept provides the methodology for quantifying the effectiveness of safety measures regarding risk, which is desired from a mathematical point of view. A standard Bayesian Network corresponding with a standard risk analysis for basic events may be expressed as:

Considering the previous, it may be assumed that the Bayesian Networks are not only an effective tool for narrowing the gap between the probabilistic and

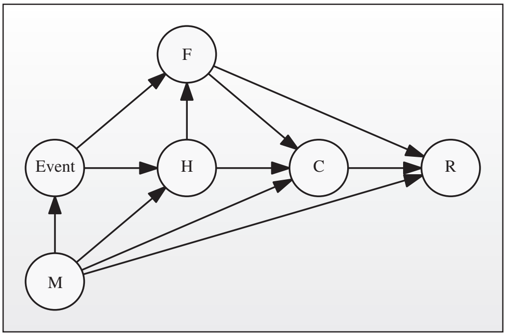

Figure 6. A standard Bayesian Network for risk analysis.

deterministic risk analysis, but Bayesian Networks are useful for combining psychological and mathematical approaches towards risk (analysis). For a case study of such an approach, see paper; Suddle, S.I., *Safety assessment of third parties during construction in Multiple Use of Space using Bayesian Networks*, this proceedings.

4 CONCLUSIONS

Considering the title of this paper "the safety of risk or the risk of safety?", it is recommendable to observe both components in safety assessment studies. Regarding the safety of risk it is common to objectify the safety in terms of risk with mathematical approaches (*the sum of probability* $\times$ *consequences*) instead of psychological one. In this regard the risk (of the safety) can be computed. In contrast, the safety of the risk characterises the opposite approach. For the safety of the risk it is recommended to take psychological definitions in consideration in risk management process. Therefore one has to combine all risk elements *with the monetary value per considered loss*.

Hence, one can accomplish all risks in one (monetary) dimension including psychological aspects. In this paper an approach for the integration of both mathematical and psychological definitions is proposed. Such integration can be accomplished with the use of Bayesian Networks. Moreover, these networks provide transparency and consistency to the risk analysis and are useful to both probabilistic and deterministic risk analysis and to combine both mathematical and psychological definitions of risk in a risk management process.

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