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Perspective

The Role of Time in Risk and Risk Analysis: Implications for Resilience, Sustainability, and Management

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There is a persistent misconception that risk analysis is only suited for considering the immediate consequences of an event. Such a limitation would make risk analysis unsuitable for many challenges, including resilience, sustainability, and adaptation. Fortunately, there is no such limitation. However, this notion has stemmed from a lack of clarity regarding how time is considered in risk analysis and risk characterization. In this article, we discuss this issue and show that risk science provides concepts and frameworks that can appropriately address time. Ultimately, we propose an adjusted nomenclature for explicitly reflecting time in risk conceptualization and characterizations.

KEY WORDS: Definition of risk; foundations of risk; risk concept; time

1. INTRODUCTION

The risk assessment process, outlined in Kaplan and Garrick (1981), seeks to answer the following questions: "What can go wrong," "what are the consequences," and "what is the likelihood?" A fourth question has also been proposed: "Over what time frame?" (Haimes, 2009). However, Haimes (2009) is only referring to one of two necessary temporal considerations:

(1) The period of time over which the activity is observed.
The second consideration is:

(2) The length of time, after an event occurring, for which we evaluate the consequences of that event.

To illustrate these two temporal dimensions, consider two illustrative examples of risk analysis. The first is the health risk for a person and the second is the risk to a seaside community. In the first case, we could consider the health risk for a person for the rest of their life. In this case, the time frame is well defined: it is their lifetime. The time over which we consider events and consequences is bounded. However, what if we consider their health risk over a 10-year period; what happens if a disease is contracted that has consequences beyond that 10-year period?

Alternatively, consider the threat of hurricanes to a coastal community. We could consider hurricanes that occur within a five-year period, but what about the long-term and indirect consequences of these hurricanes that exceed five years? How do we compare interventions that may manifest quite differently over the long term if we do not consider these long-term consequences?

In this discussion, we are not referring to periodically updating an analysis as new information arises. This is an intuitive operational procedure for an

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analyst. Instead, we refer to how these different temporal aspects are reflected in the concept of risk and how it is represented and described. As in situations such as these two illustrative examples—common throughout problems tackled by risk analysts—we must be explicit in how we address time, so it is clear to what consequences and time period our analysis refers. However, both time considerations are often omitted in how the risk concept and description are notationally defined and in much of the wider risk conversation.

This does not mean that risk analysts are ignoring time; some are not. Consider the Yucca Mountain Nuclear Waste Site risk-assessment (Ho, 1992). In this analysis, the risk assessment extended for 10,000 years. Clearly, time was an important and explicit factor for the risk analysis. In fact, all risk analysts are making decisions about how they address the temporal dimensions in their problems. However, there is the potential that these decisions are being made without consideration or awareness of how a seemingly arbitrary decision could affect the conclusions of the analysis. Clarifying the nomenclature with respect to time is therefore essential to ensure that these methodological decisions are made explicit and can be guided by research.

This formalization can also help to avoid more general confusion regarding when risk analysis is suitable. One such confusion has resulted in calls to diverge resilience analysis from risk analysis. This divergence is sometimes motivated by the argument that risk is simply referring to the "total reduction in critical functionality" (Linkov et al., 2014; Linkov, Trump, & Keisler, 2018). This metric removes the temporal dimension and lacks reference to the uncertainties relating to this reduction. However, this omission means that a system's recovery or the temporal distribution of consequences is not pertinent or of interest to risk-informed decision-making and risk analysis generally. Surely few would agree that this is the case (see Aven, 2019).

If, as many risk analysts would agree, a goal of risk analysis is to support decision-making, we need to clearly address the role of time in risk analysis. Without such clarity, there is the potential to ignore how the consequences of activities and events, interventions, or decisions evolve over time; making risk analysis a short-sighted decision-making tool. Challenges such as resource depletion, urban planning, nuclear waste management, and climate change all have deeply inherent temporal considerations (Ahearne, 2000). If risk analysis is to address these challenges, it must be explicit in how it addresses time.

The purpose of this article is to gain new insights about how time is considered in risk and risk analysis, following the discussion above. More specifically, we propose an adjusted nomenclature for explicitly reflecting time in risk conceptualizations and characterizations.

The following analysis is based on the general conceptualization of risk, recently presented in the Society of Risk Analysis's glossary (SRA, 2015):

> Risk is the consequences of an activity and associated uncertainty (1)

The SRA glossary (SRA, 2015) enumerates several related definitions of risk, which reflect the same underlying ideas as (1); they are all specific cases of (1). Consequently, the coming analysis also applies to these specific formulations of the risk concept. This conceptual definition (1) extends the idea of Kaplan and Garrick (1981) that risk is qualitatively defined as "uncertainty + damage." From the qualitative definition of risk, different types of risk descriptions and metrics can be used, as in Kaplan and Garrick (1981), which highlights events/scenarios, consequences, and probability. A more general formulation for the risk description (Section 2.2) is also presented in the SRA (2015) glossary that allows for measures and characterizations of uncertainty other than probability, see also Aven (2016). As will be discussed in Section 4, the results obtained in the article are applicable to most current perspectives on risk.

2. AN ADJUSTED RISK NOMENCLATURE

2.1. The Concept of Risk

The concept of risk allows us to discuss whether we face risk Fig. 1. As introduced in Section 1,

> *Risk is the consequences (C) of an activity and associated uncertainties (U).*

Risk is discussed in the context of some activity, for example, the operation of a system, life on earth, an investment, an ecosystem, or a community. The conceptual definition is schematically written as $\text{Risk} = (C, U)$. Without loss of generality, we can also write $\text{Risk} = (A, C, U)$, which highlights that consequences (C) and uncertainties (U) exist with respect to events (A), as shown in Fig. 1. This notation indicates that risk is a two-dimensional combination that

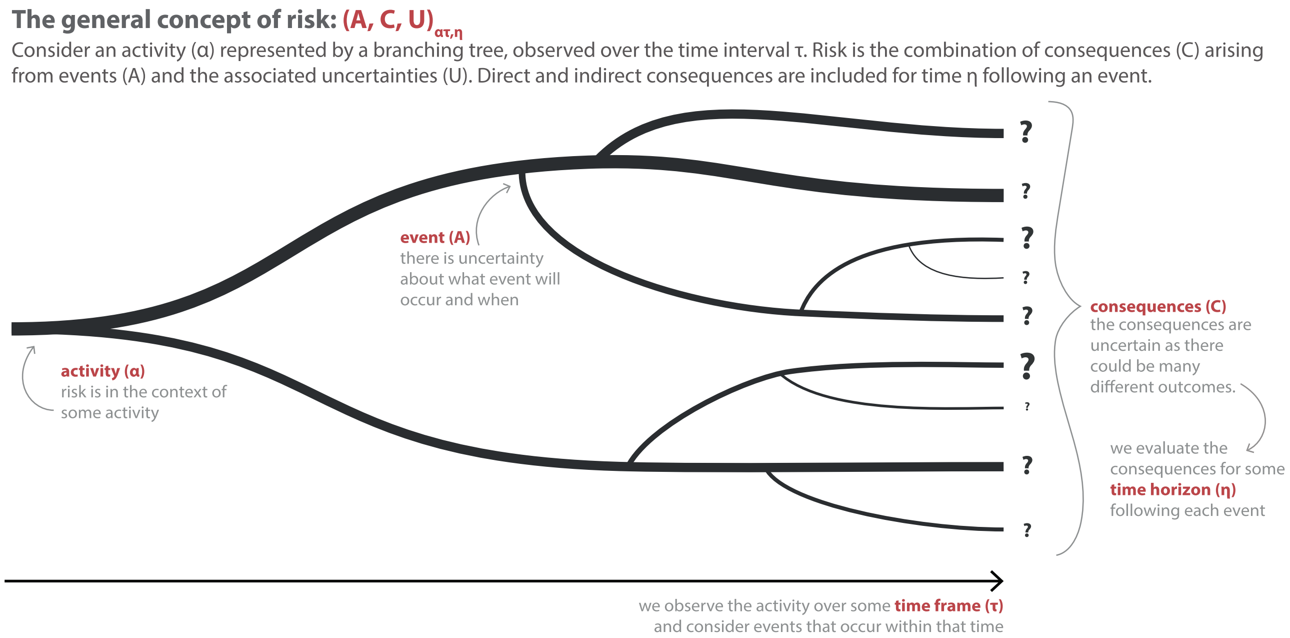


Fig 1. Illustration of the concept of risk.

includes (i) that the activity considered incurs consequences (good and bad) (C) and (ii) that there are associated uncertainties (U) in the magnitude and occurrence (Aven, 2015). It is necessary to emphasize that this notation is not providing a mathematical functional form for risk, but rather represents that risk is a combination of consequence and uncertainty.

When discussing whether we face, or an activity involves, risk, the important aspects are the consequences, the uncertainty, and the time interval considered over which the activity is observed Fig. 1. The uncertainty (U) reflects that today we do not know if or when an event will occur, nor do we know what the consequences due to these events will be. In (A, C, U), the consequences (C) relate to what may happen following the occurrence or not of events (known and unknown types). When writing (C, U), the consequences (C) may be considered as everything that happens as a result of the activity considered or they may be restricted to focus on certain aspects, for example, specific consequences (such as the loss of life) or specific events (e.g., the risk from hurricanes).

Ultimately, any discussion of risk pertains to a "specified period of time" (Aven, 2015, p. 14), whether that is a specified interval or indefinitely. Therefore, it is critical for risk analysis that our consideration of time be clarified. In Section 1, we introduced two important temporal considerations:

1. The period of time over which the activity is observed.
2. The length of time, after an event occurs, for which we evaluate the consequences of that event.

To allow us to discuss whether we face risk (the purpose of the risk concept), both temporal aspects need to be clarified.

To address the first consideration, we propose that the time interval over which the activity is considered is made explicit. We denote the activity considered as α. When observed over a time interval $[0, \tau]$, we write α_τ. Therefore, to denote that the risk is pertinent to an activity (α) over the time interval $[0, \tau]$, we write

$$\text{Risk} = (C, U)_{\alpha_\tau}$$

In Fig. 1, we see this time component moving from left to right and we consider events occurring during this time period.

This time interval ($[0, \tau]$) may be predetermined or dependent on the events that occur. That is, there are a number of possibilities for how we might define the activity and period of time (α_τ). For example, we can consider the risk for

- a community over a fixed time period (T). Therefore, $\tau = T$,
- a person for as long as they live: τ is unknown,

- a process plant over a fixed time period (T) or until the occurrence of a major event (at time T_e): $\tau = \min\{T, T_e\}$,
- a system observed for a fixed time period (T) if the system is functioning normally at time T; otherwise, it is observed until time $T + S$ (where S could be either the unknown time until the system resumes normal function or a specified time period). $\tau = T + S$ (where S=0 if the system is functioning normally at time T).

These are some examples that demonstrate that the time interval may be specified in different ways. The important point is that we are clarifying the time interval in each situation.

It is also important to address the time horizon for which we consider consequences, separate from τ, when discussing whether we face risk (the risk concept). For example, if a loss of life occurs 10 years after the occurrence of an event but the time interval (τ) ends before then, do we face risk? If Fig. 1 represented an activity where a disaster occurred moments before the end of the time interval τ, are the consequences of this disaster excluded because they fall outside this interval? How long into the future do we consider the consequences of an investment or another decision? Both the activity and the event could be instantaneous, but the consequences may be far-reaching.

We introduce the quantity η to represent the time, beyond the occurrence of an event, that consequences are considered. Both τ and η are needed to specify when risk is considered (faced). Therefore, we write that

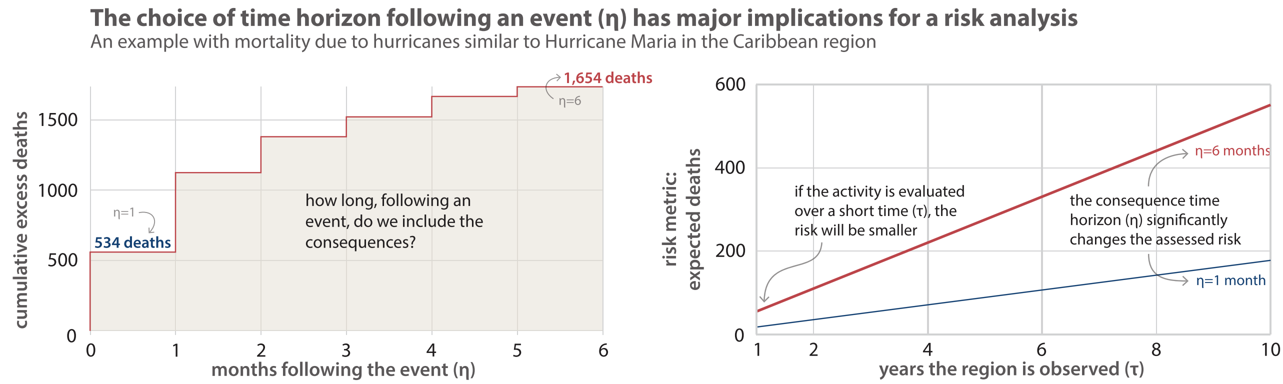
$$\text{Risk} = (C, U)_{\alpha_\tau, \eta}.$$

This notation expresses that the activity is considered over a time interval $[0, \tau]$ and η specifies the time over which the consequences are considered, following the occurrence of an event. There are alternative ways in which we may wish to formulate the time horizon for consequences that may be preferable in different situations. For example:

- We may want to know the risk that someone may die within a certain time after their being exposed to some toxin. E.g., we can calculate the risk of death within 10 years ($\eta = 10$) if someone is exposed to a toxin for five years ($\tau = 5$).
- We could consider the consequences of an event over a fixed period from the occurrence of that event. E.g., we include the direct and indirect consequences of a hurricane over the five years following the hurricane. Therefore $\eta = 5$.
- We can generalize the previous example and allow the fixed period to be different for each event. In this case, we allow η to be a vector such that η_i represents the time after the occurrence of event *i* over which we evaluate consequences.
- Alternatively, we may want to consider the consequences until the end of the period that the activity is observed. Therefore, we write $\eta = \tau - t$, where t is the time of the event. If there are multiple events then, again, η may be a vector and we write $\eta_i = \tau - t_i$, where t_i is the occurrence time of each event.
- We may want to consider the consequences for a number of years beyond the period over which we observe the activity. For example, let X be the time following the conclusion of the interval $[0, \tau]$. Thus, $\eta_i = \tau - t_i + X$.
- Both τ and η could be infinite.

Using the examples provided earlier for τ, we consider the risk for:

- a community over a fixed time period ($\tau = T$) and include only immediate effects of events. Therefore, $\tau = T$ and $\eta = 0$;
- a community over a fixed time period ($\tau = T$) and include direct and indirect effects occurring within five years of each event. Therefore, $\tau = T$ and $\eta = 5$;
- a community over a fixed time period ($\tau = T$) and include direct and indirect effects occurring up until five years after the end of the observation period ($X = 5$). Therefore, $\tau = T$ and $\eta_i = \tau - t_i + 5$, where t_i is the time of occurrence of any event;
- a person for as long as they live. τ is unknown and η is over that same time period, so $\eta_i = \tau - t_i$, where t_i is the occurrence time of an event (e.g., they contract an illness and we assess the consequences of that illness over the rest of their life);
- a person's wealth. The activity (the person working) is observed until they retire (an unknown interval $[0, \tau]$) and the consequences include their wealth, after retirement, throughout their lifetime. Therefore, $\eta = L - \tau$, where L is their lifetime, which is unknown;
- a process plant over a time ($\tau = \min\{T, T_e\}$) and long-term effects due to any events occurring in $[0, \tau]$. We write $\eta_i = \tau + L - t_i$, where L is the



(a) Excess deaths (compared to previous years) in Puerto Rico following Hurricane Maria in 2017.

(b) Risk, measured as expected deaths, in the Caribbean region from hurricanes similar to Hurricane Maria. The return period is based on an assessment by KCC (2017).

Fig 2. Illustration of the role of η (the time to consider consequences following an event) versus τ (the time over which an activity is observed) in risk and risk analysis.

length of the long-term effects and can be specified;

- a system considered for a fixed time period ($\tau = T + S$) as explained above, with the consequences also covering effects in a 10-year period following τ (i.e., $X = 10$). Thus, $\eta_i = \tau - t_i + 10$, i.e., the time following an event over which its consequences are considered (η) is the time until the system is functioning normally ($\tau = T + S$), minus the time of the event (t_i), plus some period following normal function (X).

To illustrate the first two of these examples, see Fig. 2. That is, there is a community threatened by hurricanes and we are assessing the risk to that community. In Fig. 2(a), we present the cumulative number of excess deaths (those that would not have occurred otherwise) following the 2017s Hurricane Maria in Puerto Rico; deaths rise over time due to, in addition to direct deaths (e.g., fallen trees or flooding), the prolonged subsequent disruption that can lead to indirect deaths (e.g., due to infrastructure failures or impacts on water quality) (Kishore et al., 2018). In these instances, the relative excess mortality ratio can be significantly higher for the lower socioeconomic classes (Milken Institute, 2018). Fig. 2(a) pertains to the selection of η: over what time period (following an event) will consequences be considered? The uncertainty—due to the contention over Hurricane Marias death toll (Milken Institute, 2018; Kishore et al., 2018; Robles, Davis, Fink, & Almukhtar, 2017)—is omitted for the examples clarity. Fig. 2(b) shows how this choice has a substantial impact on subsequent risk assessment. To demonstrate and simplify the discussion, we measure risk as expected loss of life, calculated by multiplying losses with associated probabilities and summing over all loss values. If η is lower, the risk is lower. Fig. 2(b) also shows the impact of τ (the time over which an activity is observed) on the assessed risk; the longer this interval the more likely it is that a hurricane will occur within that time, and so the risk is higher. Both temporal aspects clearly have implications for the risk analysis.

This notation

$$\text{Risk} = (C, U)_{\alpha_\tau, \eta}$$

clarifies the role of time in the general conceptual definition of risk. This adjusted notation reflects that both the time over which we observe the activity and the time over which we consider consequences have a major influence on whether we determine if a system induces risk.

2.2. The Risk Description

While the concept of risk enables us to say whether or not we face risk, the description of risk enables us to express how large the risk is. As we have adjusted the nomenclature for the concept, now we turn to the nomenclature for the description of risk.

In general terms, following the SRA (2015) glossary, the description includes:

- the specified type(s) of events (A'),
- the specified type(s) of consequences (C'), and
- an associated uncertainty characterization (Q and K), where

- Q is a measure (interpreted in a wide sense) of uncertainty, and
- K is the knowledge upon which the assessment of the consequences and uncertainty is based.

For short, we write (A', C', Q, K) or simply (C', Q, K) (Aven, 2015). This triplet summarizes, in general terms, the key components required to describe risk, which allows one to conduct a qualitative or quantitative risk assessment.

Again, time is omitted. Yet, clearly, the time over which an activity is observed and the time horizon that consequences are considered are critical factors in determining the magnitude of risk. We resolve this in a manner consistent with the proposed concept of risk; that is, the description of risk should include:

- the time interval over which the activity is observed and
- the time horizon, following an event, over which the consequences are included.

We suggest that this is also written as

$$(C', Q, K)_{\alpha_\tau,\eta}.$$

For example, to describe the risk for a community, we need to know the following: the time period that the community is observed, the type(s) of events that we are assessing (e.g., hurricanes), the length of time following an event's occurrence over which we include consequences (e.g., two years), the type(s) of consequences we consider (e.g., fatalities and economic loss), the measure of uncertainty we will use (e.g., probability of a hurricane occurring in any given year, with related strength of knowledge judgments), and the knowledge upon which we base the assessment of the consequences and uncertainty measure (e.g., data, information, justified beliefs, assumptions, etc.).

One example of strength of knowledge judgments as referred to here is the qualitative assessment scheme described by Flage and Aven (2009). In this scheme, the risk analyst makes judgments relating to the understanding of the phenomena involved and models used, as well as relating to data and expert judgments, and assumptions made. These judgments result in a categorization (strong, moderate, or weak) of the strength of the knowledge involved.

Some illustrating examples of the risk concept and description are provided in the following section.

3. ILLUSTRATING EXAMPLES

3.1. John's Illness

We consider the health condition of a person, John, as a result of the potential occurrence of a specific disease (D). While the level of detail we provide in this example may seem excessive, it avoids potential confusion and will provide a basis for the latter examples. We define the following:

α_τ: We observe the activity (John living) over a time interval of one year.
η: We assess the consequences of John contracting the disease over the course of 1 month, 1–12 months, the remainder of his life.

Risk

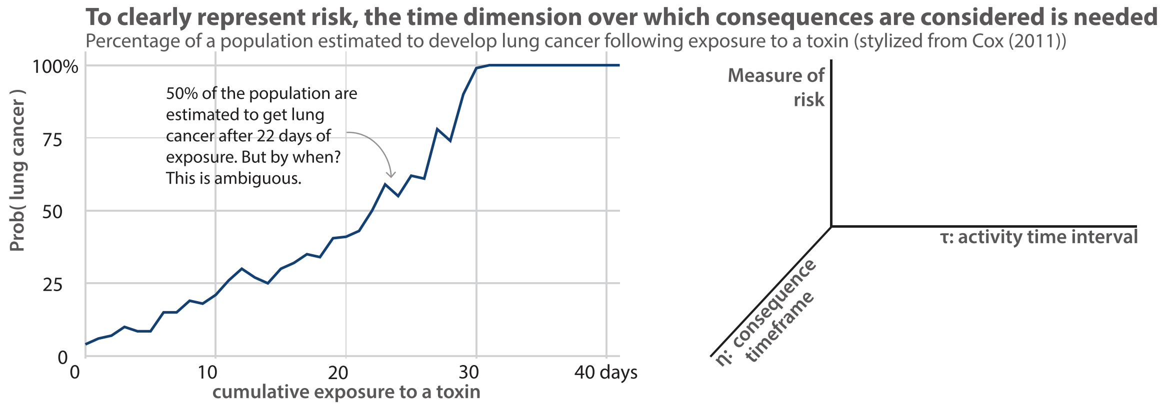
A: The event is John contracting the specific disease D or not, within the year observed.
C: The consequences to John from the disease within the specified time intervals η (he may die, suffer, etc.).
U: Today we do not know if John will contract one or more of these illnesses, and we do not know what the consequences (over the time intervals η) will be.

Risk description

A'_1: John contracts the disease that year.
A'_2: John does not contract the disease that year.
C': John's health state within each of the time intervals considered, e.g., John dies within 1 month.
Q: We choose to express the uncertainty using probability with judgments of the strength of the knowledge supporting the probability assignments.
K: The knowledge on which the elements $(A', C', Q)_{\alpha_\tau,\eta}$ are based.

3.2. Exposure/dose-Response

Modifying our example in 3.1, we now consider the health of a population exposed to some toxin. We adapt the specifics of this example from Cox (2011). Cox (2011) looks at whether crystalline silica exposure increases the risk of lung cancer. The probability of cancer developing is used as a measure of risk. Fig. 3(a), adapted from Cox (2011), shows

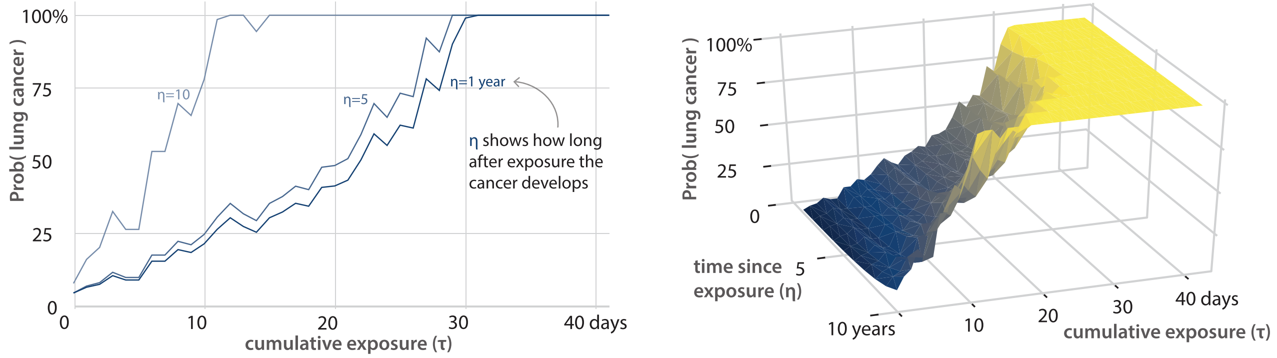


To clearly represent risk, the time dimension over which consequences are considered is needed

Percentage of a population estimated to develop lung cancer following exposure to a toxin (stylized from Cox (2011))

(a) The traditional approach showing both risk and its dependence on the time the activity is observed

(b) We recommend a new dimension of time, η, to represent when consequences are considered



(c) We can represent this new time dimension for the consequences (η) discretely

(d) Alternatively, we can represent the time dimension for the consequences (η) continously

Fig 3. An example of why clarifying how time is considered is important in risk analysis. This is a stylized exposure–response relation for a population of people exposed to a toxin. This shows the importance of including the time over which consequences are considered, which is ambiguous in Fig. 3(a). In Figs. 3(b), we introduce the second time "dimension," and in Figs. 3(c) and (d), we demonstrate this both discretely and continuously. Note that in this situation, probability is used as the *measure* of risk.

how this risk increases with exposure time. However, the time over which consequences are considered is ambiguous. That is, the analysis suggests that 50% of people will develop lung cancer following 22 days of exposure, but within what time frame? For example, does the cancer develop immediately or within their lifetime? Our proposal seeks to clarify this in future analyses.

In Fig. 3(b), we show how the time over which consequences are considered can be reflected. The risk is a function of both the cumulative time of exposure (τ) and the time considered following that exposure (η). The probability of developing cancer increases with η, as illustrated by the hypothetical examples of Figs. 3(c) and (d), showing a discrete and continuous representation, respectively. For example, while exposure to a (hypothetical) toxin after 14 days results in a 25% probability of developing cancer within one year, the probability of developing cancer increases to 30% and 95%, within 5 and 10 years, respectively.

To represent this within the proposed risk notation, we define the following:

α_τ: We observe a group of people exposed to crystalline silica over a period of τ days.

η: We assess the consequences to these people continuously over the course of η years. Note that in this example, we vary both τ and η, so the reported risk is a function of both.

Risk

A: The event coincides with the end of the activity: someone's exposure to crystalline silica over τ days.

C: The percentage of the population that develop lung cancer within T_c time since their exposure.

U: Today we do not know if they will develop lung cancer within the specified time (η).

Risk description

A': Exposure to crystalline silica accumulated over i days.
C': The percentage of the population who develop lung cancer within T_c time since being exposed to crystalline silica for i days.
Q: We choose to express the uncertainty using probability specified on the basis of the observed percentage of the population who develop cancer.
K: The knowledge on which $(A', C', Q)_{\alpha_\tau,\eta}$ are based.

3.3. A Community Threatened by Hazards

Now we consider a community at risk from hazards. We define the following:

α_τ: The community (where we specify the boundary and components considered: e.g., an urban system, demographic of customers and their electrical infrastructure, etc.) over a period of time. In this case, consider the residents within the city limits of a specific community and their access to food stores including the transport system and systems required for the operation of the store. The interval considered is one year.
η: We assess the consequences every day until the system has returned to its state predisruption (alternatively, we could assess the consequences every day over a fixed period to examine the postevent transformation).

Risk

A: The community is impacted by a specific hazard or not within the year observed.
C: The consequences to the community and the residents' access to food within the time it takes to return to the preevent state.
U: Today we do not know if a hazard will strike the community within the year, nor do we know what the consequences will be until the system is restored to its preevent state.

Risk description

A'_1: A category 1 hurricane occurs during the year.
A'_2: No hurricanes of category 1 occur during the year.
Note: The analyst can choose what specific events they consider (e.g., other categories of hurricanes, different hazards, etc.).
C': The area above the recovery curve. This represents a measure of the decrease in system functionality integrated over the time it is in that substandard state. For example, Fig. 4 shows the proximity to the average distance to the nearest operational store for two amenities during a hurricane.
Q: We choose to express the uncertainty using probability with judgments of the strength of the knowledge supporting the probabilities.
K: The knowledge on which $(A', C', Q)_{\alpha_\tau,\eta}$ are based.

In this instance, we define the consequence as including both direct and indirect outcomes that occur until the system/community has recovered. Therefore, in contrast to perspectives where risk interventions are focused solely on reducing immediate disruption, the risk handling here could relate to actions and interventions that influence the speed of recovery. Similarly, actions that reduce future consequences through adaptation or transformation are equally pertinent to risk-reducing strategies.

How we have defined the consequences and η here is just one example. For instance, an alternative is to define the consequence as the maximum loss in functionality (again, over the time until the system has recovered); this would be useful for situations where catastrophic failure occurs below some level of system function (e.g., a nuclear plant). Both are examples of the ways we can define the consequence in a risk analysis—what is critical is that the manner in which these temporal considerations are managed is clearly stated.

3.4. Nuclear Waste

As a final example, we present the risk assessment into the Yucca Mountain nuclear waste site (Ho, 1992). This is an example where the consequences are limited to being a binary occurrence: the disruption, or not, of the nuclear repository. Risk assessments of this nature are common and easily fit within the concept and framework for considering the time dimensions that we describe. In this

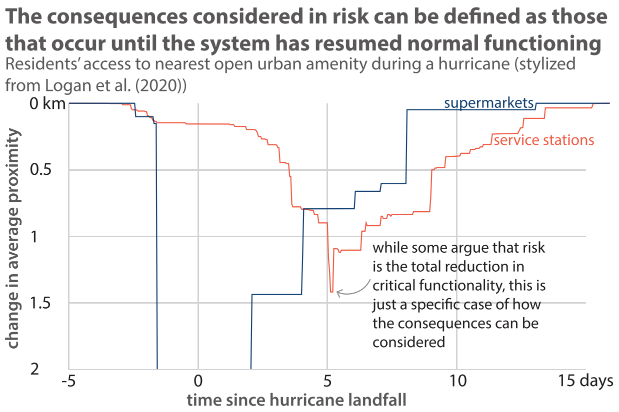


Fig 4. An example showing how the time period over which the consequences are considered (τ) could be defined. This is a stylized recovery/resilience curve for a community impacted by a hurricane (based on Wilmington, NC, during Hurricane Florence in 2018 (Logan & Guikema, 2020). The time to consider consequences is, in this case, up until the system has returned to normal functionality. Alternatively, it could be expressed as the maximum loss of system functionality.

assessment, they assessed the likelihood of an eruption occurring and disrupting the waste site.

We define:

α_τ: The radioactive decay of nuclear waste over the recommended isolation period of 10,000 years. So, we consider events over that time interval.

η: The time following an event until it no longer threatens to disrupt the site.

Risk

A: A volcanic eruption within 10,000 years.

C: The disruption of the nuclear waste repository.

U: Today we do not know if an eruption will occur within the specified time interval or whether it would be large enough to disrupt the waste site.

Risk description

A': A volcanic eruption occurs within 10,000 years.

C': The nuclear waste site is disrupted or not. In Ho (1992), the implications of such an eruption were not considered.

Q: Ho (1992) expresses the uncertainty as a probability to represent both whether an eruption occurs and whether the repository is disrupted given this eruption. Additionally, we should include judgments of the strength of the knowledge supporting these probabilities.

K: The knowledge on which $(A', C', Q)_{\alpha_\tau,\eta}$ are based.

The example, based on Ho (1992), demonstrates that risk analysts are already considering the risk over long, intergenerational time periods. What we offer in this article is a formalization of how time should be incorporated into and addressed in all risk analysis applications for their clarity.

4. DISCUSSION

There are major implications invoked by making time explicit in the conceptual definition and description of risk, specifically regarding the length of time the consequences are considered (η) in some circumstances. Explicitly framing time in the concept and description of risk means that issues regarding sustainability and intergenerational justice must be considered for long-term issues such as nuclear waste management and climate change. Intergenerational equity is a major factor in the discussions around climate change, other environmental crises, resource use, nuclear waste, nuclear weapons, and population growth (Ahearne, 2000). These decisions have far-reaching consequences and for every situation, there are different appropriate planning-horizon lengths (Starr, 2000; Svenson & Karlsson, 1989). One ethically controversial discussion surrounding long-term decision making is the discounting of consequences (Belzer, 2000; Okrent & Pidgeon, 2000; Schelling, 2000; Shrader-Frechette, 2000; Svenson & Karlsson, 1989). Some argue that discounting is unavoidable (Belzer, 2000), while others point out that discounting consequence can result in policy choices that simply transfer risk rather than address it (Shrader-Frechette, 2000). Discounting may lead to a low level of investment in long-term risk treatment and adaptation options (Espinoza et al., 2020).

Considering time therefore raises foundational questions for risk science. What guidance can we provide regarding the choice of the temporal intervals for observing the activity (τ) and considering the consequences (η)? What are the implications on the risk assessment and subsequent recommendations? How do we communicate uncertainty and small probabilities in a long-term risk context (Svenson & Karlsson, 1989)? What frameworks exist for intergenerational decision-making situations (Aven & Zio, 2014)? What guidance is available for determining whether, how, and under what circumstances, discounting should be used? Should, and if so how should, the time horizon be chosen over which to estimate consequences? Thompson, Maguire, and Regan (2018) addressed the question of discounting in a way that avoids an arbitrary time horizon in the case of species extinctions. Additionally, acknowledging the temporal dimension also raises the question: Should disaster-response assistance be focused on those who have been directly affected by the event, or should the emphasis be on reducing the risk for future generations? (Glantz & Jamieson, 2000). Explicitly including time in the notation of the concept and description of risk encourages such discussion and consideration in future risk analysis work.

Additionally, acknowledging the temporal dimension has implications for resilience analysis and sustainability. For example, if the consequences of an event are affected by the recovery, then risk reduction interventions also include improving the capacity to recover. It again raises the intergenerational question as to whether disaster response should be focused on short-term recovery and defense or long-term improvements (Glantz & Jamieson, 2000). This means that adaptation and transformation of systems are critical to, not only resilience (Béné, Wood, Newsham, & Davies, 2012) but risk analysis. The decisions made following an event have implications for, not only the recovery but also the systems future exposure and vulnerability. In this way, an appropriate, long-term view, means that risk analysis can guide decisions such as those pertaining to climate adaptation and sustainability.

Appropriate consideration of these time components has implications also for other risk analysis aspects, including applied risk management. The risk management process addresses questions such as (Haimes, 2009):

(1) What can be done and what options are available?
(2) What are the trade-offs in terms of all relevant costs, benefits, and risks?
(3) What are the impacts or current decisions on future options?

Critical to addressing these questions is understanding the potential consequences. To do this in a manner suitable for decision-making, it must be clear what time period the presented consequences are pertaining to. For example, when comparing alternative interventions, it is possible that the time horizon over which consequences are determined will influence the rank order of these interventions; that is, one may be preferable in the short term but detrimental in the long term. Thus, it is critical that the time horizon used is clearly stated for decision-makers.

By clarifying the role of time in the concept and description of risk, risk science can be more definitive in future research and practice. This may help quell the confusion associated with subfields, suggesting that they diverge from ours (e.g., "resilience analysis"). However, the common failure to distinguish between the definition and description is another factor contributing to the confusion and is one we now briefly address. To help limit this confusion, it would be highly beneficial if risk researchers distinguish between their adopted concept and their chosen measure of risk (Aven, 2016). As one example, a recent publication in this journal defined risk as "risk is the probability of an unwanted event." However, rather than the definition of risk, this is the measure they have chosen to use. This type of confusion can lead people to think that risk analysis is unsuitable for some types of analysis. To prevent this, we encourage authors to clearly distinguish between their *measure* and their *definition* of risk. A simple intervention for risk science's benefit would be that the *Journal of Risk Analysis* and other risk journals request their authors to make this distinction clear.

Nevertheless, the main contribution of the present article is proposing how to explicitly include time in risk analysis and therefore pertains to all definitions and measures of risk. If a framework is adopted in which risk is understood by reference to, for example, a probability of an unwanted event (as defined above), or the Kaplan and Garrick (1981) triplet (events/scenarios, consequences, probability), the general principles for risk descriptions in Section 2.2 still applies, even if a qualitative definition is not introduced. The framework clarifying the temporal dimensions we present is therefore suitable for most common risk perspectives.

5. CONCLUSION

To clarify the role of time in risk analysis, we have proposed updating the nomenclature for the risk concept and description. In doing so, and without loss of generality, we argue that risk analysts should specifically define the activity over which the risk is considered, the time over which this activity is observed, and the period over which the consequences are considered following an event. The result is that the concept of risk can be expressed:

$$\text{Risk} = (C, U)_{\alpha_\tau, \eta},$$

where

$\alpha_\tau =$ the activity or system (interpreted in a wide sense to also cover, for example, natural phenomena such as an ecosystem) and the time interval ([0,τ]) over which it is observed (e.g., the functioning of a community over the next 10 years) and events are considered
$\eta =$ the time horizon(s) following the occurrence of any event for which consequences are considered (e.g., one month, one year, and five years),
$C =$ the consequences over the specified time horizon (η), and
$U =$ the uncertainty associated with the events and their consequences.

Analogously to the concept of risk, we update the notation for the risk description to reflect the temporal dimension such that:

$$\text{Risk description} = (C', Q, K)_{\alpha_\tau, \eta},$$

where

$C' =$ the consequences over the specified time horizon (η),
$Q, K =$ the characterization of the associated uncertainty, where Q is the measure of uncertainty, and K is the knowledge upon which the assessment is based.

Using this terminology means that the decisions related to the temporal dimensions, already being made when estimating consequences in a risk assessment, are now clear in the notation.

This notation for the assessment period of the consequence confirms that time is an essential consideration. It means that a system's recovery can significantly affect the consequences from an event and clarifies that the risk analyst's purview includes more than robustness. Recognizing the role of time also enables discussions regarding the potential trade-offs and ethical decisions between the present and future generations affected by the risk analysis. This long-term formulation of risk means that sustainability is well within the risk analyst's remit. Additionally, this encourages further research into foundational questions that can provide guidance to analysts regarding how to incorporate time. Exploring these questions is especially necessary so that risk is equipped to address complex questions with intergenerational implications (including resilience analysis, justice, and sustainability) that are among the most pressing of our time.

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