Safety and Reliability

Explicit and implicit inclusion of time in the definitions of risk and reliability

--Manuscript Draft--

Full Title:	Explicit and implicit inclusion of time in the definitions of risk and reliability
Manuscript Number:	TSAR-2020-0003R3
Article Type:	Technical Paper
Keywords:	Risk; Reliability; Time
Manuscript Classifications:	Reliability; Risk
Abstract:	In safety, understanding of risk and reliability is generally not possible without reference to time. For example, regarding the risk of some activity or situation, focus is on what might happen in future time in relation to the potential for negative outcomes or consequences. Currently, several definitions of risk are available, indicating a lack of consensus on how to define this, also within international standards. A common characteristic, is that neither of the definitions are explicitly capturing time. In contrast, the concept of reliability is explicit on this, focusing on failure-free performance for a given time interval, indicating a discrepancy and inconsistency between the concepts. There are different temporal aspects and key argumentation for and against inclusion of time in the definition of risk. We discuss the relevance to the understanding and interpretation, and conclude, that it is insufficient to assume time strictly implicitly as part of the possible consequences. As for the reliability concept, the element of time matters to the understanding of risk as a concept, and contributes to a more specific description of risk. A more appropriate definition of this concept that allows for this element to be explicitly captured is suggested in this article.
Order of Authors:	Jon Tømmerås Selvik, Ph.D.
	Eirik Bjorheim Abrahamsen
Response to Reviewers:	The sentence on page 11 (line 46), is changed from what was in the original version: … 'risk description measures, we have provided limited discussion on what is effect on risk description.' to what is now (as suggested by the reviewer): 'risk description measures, we have provided limited discussion on what the effect is on risk description.' Thank you for pointing out that we inserted the wrong sentence in the previous document.

Explicit and implicit inclusion of time in the definitions of risk and reliability

J. T. Selvik and E. B. Abrahamsen,

Dept. Safety, Economics and Planning, University of Stavanger, Norway

Abstract

In safety, understanding of risk and reliability is generally not possible without reference to time. For example, regarding the risk of some activity or situation, focus is on what might happen in future time in relation to the potential for negative outcomes or consequences. Currently, several definitions of risk are available, indicating a lack of consensus on how to define this, also within international standards. A common characteristic, is that neither of the definitions are explicitly capturing time. In contrast, the concept of reliability is explicit on this, focusing on failure-free performance for a given time interval, indicating a discrepancy and inconsistency between the concepts.

There are different temporal aspects and key argumentation for and against inclusion of time in the definition of risk. We discuss the relevance to the understanding and interpretation, and conclude, that it is insufficient to assume time strictly implicitly as part of the possible consequences. As for the reliability concept, the element of time matters to the understanding of risk as a concept, and contributes to a more specific description of risk. A more appropriate definition of this concept that allows for this element to be explicitly captured is suggested in this article.

Keywords: Risk, Reliability, Time, Safety, Future, Consequences, Uncertainty

1. Introduction

Risk is occupied with strictly one temporal realm; i.e. the future. The concept of risk is about the possible consequences that could occur in future time with respect to some activity or situation. Extensive literature discusses the concept by addressing how it is appropriate to express "what will occur and be the consequences" (see e.g. ISO 31000:2018; ISO/IEC Guide 51:2014; Cox 2002, p.8; and Aven 2015, p.13). In particular, some advocate a probabilistic risk concept, while others advocate a broader uncertainty concept. This is also the current situation in risk-related international standardization documents. So far, there are clearly different opinions within the risk community on this issue, and a variety of definitions exist (outlined briefly in Section 2).

In the current article, our primary focus is not on the aspect of what can happen, but rather on the question of whether, and if so, how, the element of time should also be included as a more explicit part of this equation; aspects that seems somewhat hidden or ignored in risk management literature and international standards. Despite some, for example Haimes (2016), Yang and Haugen (2015) and Paltrinieri et al. (2014), and several others, are pointing to the importance of considering time frame in risk assessment, this is typically not related to the consequences but, rather, to the activity or performance of the system (e.g. society) at risk and the timing of updating knowledge. There are several studies addressing the relationship between time and risk in a dynamic risk assessment context, which become highly relevant under increasing digitalization, as indicated in Zio (2018). For example, Yang et al. (2018) studies the distinction and use of real-time, dynamic and operational risk, which all relates to the aspect of time. Paltrinieri et al. (2014) studies the use of dynamic risk assessment related to real-time data in the oil and gas industry, where it is claimed to be a key to continuously update risk description with relevant knowledge from the present time. Although the studies are not specifically relating time to the conceptual understanding, the importance of time in the description of risk (assessments) indicates a certain relevance.

A main motivation for studying different time aspects in this context is that, by ignoring this, one could claim that the definition lacks sufficient specificity. An important 'when' part could then be missing. Besides, it can be questioned whether it is consistent to include time frame explicitly in the reliability definition (see definition of this concept in 3.1), which is another key concept addressing what can happen in the future, but then to ignore it in the definition of the risk concept.

As one example, motivated from Barbara Adam's timescape discussion on the effects of the 1986 Chernobyl disaster effects, Adams (1998, p. 223) refer to the challenge of predicting the future. She claims from a social perspective that it is nearly impossible to establish casual relationships for such events. For example, from an extreme time perspective, one could argue that the consequence element of nuclear risk in theory could include all the associated effects in an infinite time interval, as there is a possibility of genetic effects and that children are victims of the radiation. Then, if we also include butterfly effects (i.e. the effects of the effects), we could problematize by questioning where to stop; i.e. should we go as far as also capturing the end consequences (the final effect) of the chain of events linked to e.g. a nuclear leakage. This might obviously for many situations be highly challenging or nearly impossible to assess, based on the definitions available, as we clearly might not be able to express and combine the aspects of time with societal consequences. However, this is perhaps more a challenge of expressing the risk (i.e. risk description), and not as much related to the basic understanding of the risk, although the period (time frame) defined clearly influences the level of risk and interpretation. For example: what are the risks and consequences of air pollution? Given our knowledge, and the current pollution level, we can to some extent predict the system behaviour and effects in different time perspectives. Obviously then, the longer into the future that we try to predict, the more uncertain and complex the predictions will be. Depending on the time frame in focus, the risk could then vary significantly. For example, with respect to air pollution, some efficient cleaning technology could be developed and implemented 50 years into the future, influencing the risk.

The same applies to exposure to hazards or potential losses. The risk is obviously dependent on the time interval (frame) in which the consequences are studied. Consider for example gaming activity, where the player can experience a loss straight away (instant) or the same loss hitting half a year from now (delayed), or the amount spread out in several losses during the period, given the same uncertainty. Despite the player losing the same amount, the time aspect matters, and the time influence clearly influence the risk. Some would perhaps assume these as three different consequences. Nevertheless, it is obvious that the three scenarios are not necessarily separated based on the current risk definitions – it could be, but not necessarily.

A main objective of the current article is to identify the principal reasons for and against making the element of time an explicit part of the risk concept. Specifically, it is important to clarify what are the implications of including it, including the relationship to the reliability concept. However, the issue of how risk should be pictured in assessments is outside the scope of the discussion.

The remainder of the article is structured as follows. In Section 2, we introduce some key risk definitions. Then, in Section 3, we provide further argumentation on why the time aspect is important to the understanding of this concept, by addressing various ways that time influences risk with reference to existing literature on the issue. In Section 4, we give some specific recommendations regarding how to express and define the concept of risk. Then, in Section 5, we give an example, in which we clarify and discuss the implications of the recommended definition. Finally, Section 6 provides some brief concluding remarks.

2. The concept of risk – key definitions

The concept of risk is widely discussed in literature, partly because of the challenge within the scientific community to agree upon an appropriate and unified definition for all applications. The variety is evident from the variety of definitions given in international guidance documents issued by the International Standardization Organization (ISO) and the International Electrotechnical Committee (IEC), particularly the ISO Guide 73:2009 and the ISO/IEC Guide 51:2014.

A key definition is the one given in the joint ISO/IEC Guide 51:2014 on safety aspects, which is, according to the ISO online browsing platform, currently the most quoted risk definition amongst the ISO/IEC standards, where risk is a "*combination of the probability of occurrence of harm and the severity of that harm*". Here, the 'harm' strictly captures the consequence aspect in a safety context, and this could be extended, for other applications, to consequences in general, to capture a broader set of propositions that threaten values or objectives. These consequences are probabilistic as opposed to deterministic, and thus reflect the situation of the different possible future outcomes; typically labelled as (negative) consequences.

Further, there is the widely adopted, widely discussed, and somewhat ambiguous, definition given in ISO 31000:2018 on risk management (adopted from the ISO Guide 73:2009), where risk is "*the effect of uncertainty on objectives*". Refer also to e.g. Aven (2011) and Purdy (2010) for a discussion on the meaning of this definition. There is also a shorter version of this; defining risk as simply "the effect of uncertainty" as given in e.g. ISO 9000:2015 and ISO 30400:2016 within the management area. A link is also available in the glossary provided through the organization 'Society of Risk Analysis' (SRA) by the in-house Committee on the Foundations of Risk Analysis (2015), providing an overview of relevant but different qualitative risk definitions:

a) Risk is the possibility of an unfortunate occurrence
b) Risk is the potential for realization of unwanted, negative consequences of an event
c) Risk is exposure to a proposition (e.g. the occurrence of a loss) of which one is uncertain
d) Risk is the consequences of the activity and associated uncertainties
e) Risk is uncertainty about and severity of the consequences of an activity with respect to something that humans value
f) Risk is the occurrences of some specified consequences of the activity and associated uncertainties
g) Risk is the deviation from a reference value and associated uncertainties

Nevertheless, we see two distinct directions in conceptualizing risk. One represents the probability-oriented way, where risk is seen as some combination of the probability of an event and its consequences (C, P), including the combination or product of the two. The other is the uncertainty-oriented way, where risk is some combination of consequences and the associated uncertainties related to what will be the consequences (C, U), which provides a somewhat broader and subjective understanding of risk, and being more dependent on the social context. In many areas we have seen a shift from the (C, P) way to the (C, U) way. Such a shift is seen in the ISO 31000-standard, being is seen as very influential access different societal and industrial areas, where the 2009 edition adopted the (C, P) way.

We will not go into the discussion of which way is appropriate. Common to both directions is that risk concerns an activity within some system or frame, implicitly then also a time frame, in which consequences of a negative character (at least one) could occur, such as, for example, snow avalanches destroying buildings, oil and gas production losses, etc. If we look at this from a causality perspective, the focus is on what can go wrong or cause deviations leading to the consequences and what these are. In both directions, understanding risk is about assessing what can happen in the future and how likely this is, based on our knowledge or the information available.

Overall, the combination of probabilities and consequences is valuable and attractive, based on the link to expected value theory, which is highly favoured by economists, but is then also widely criticized exactly because of that. Haimes (2016, p.xi) points to the limited ability to express extreme event consequences when the two element C and P is combined and reduced to one number by taking the product of the two. In general, advocates of the (C, U) perspective argue that probabilities is not a 'tool' that is well suited to capture the potential for consequences. There are significant limitations in this way, and a broader concept based on the use of uncertainty instead would, according to several, e.g. Aven (2015), then be more appropriate. The replacement of the probability element with an uncertainty element forces the risk description to also capture other aspects such as the strength of knowledge and the framing of the risk situation. This could also be described adopting a (C, P) perspective, but does not have to. Still, the main focus is on what will occur and what will be the future consequences.

For simplicity we will for the discussions in the remaining of the article adopt a (C, U) perspective.

3. The relevance of time to the concept of risk

In the text above we have referred to different time aspects without any clear distinction between them, and not given any clear opinion on which ones are implicit in the risk concept. Regarding modulus of time, obviously, the matter is clear; risk is strictly concerned with *future* events, although our knowledge of the future would necessarily build on *past* and *present* knowledge.

For the purpose of identifying key arguments regarding whether time should be explicit in the risk definition, we adopt the classic timescape elements outlined by Adam (2008). These seven elements capture the time aspects relevant to our discussion. In addition to the temporal modalities past, present and future, these are:

- Time frame – bounded, beginning and end of day, year, life time, generation, historical/geological epoch;
- Temporality – process world, internal to system, aging, growing, irreversibility, directionality;
- Timing – synchronization, co-ordination, right/wrong time;
- Tempo – speed, pace, rate of change, velocity, intensity: how much activity in a given time frame;
- Duration – extent, temporal distance, horizon: no duration = instantaneity, time point/ moment;
- Sequence – order, succession, priority: no sequence = simultaneity, at same time;

Not all of these are as relevant for the conceptual understanding of risk, as for the understanding of for the dynamics of social relationships in the way Adam (2004) apply them. Hence, we ignore some of the elements. For example tempo is important for carrying out activities of risk, but not for the conceptual understanding. For the understanding of risk, we limit our attention to three overall phases related to the time aspects, which are as indicated above fundamentally very different:

a) Time of events leading to possible consequences - time frame during which the situation is occurring, or activity is performed: the exposure risk window and where the initiating events can take place in a temporal manner;
b) Time of the consequence events - the temporality and duration of the associated consequences; and
c) Time of the system framing (e.g. when undertaking a risk assessment) - i.e. timing: when the framing is performed.

In some way, all of them could somehow influence the conceptual risk understanding. In the subsections below, we briefly address the argumentation related to whether the specific time aspects should be an explicit part of the risk concept.

On the other hand, it is not too difficult to picture that there are situations where time aspects are of relevance to the assessment or evaluation of risk, but should be left out of the definition as there is no need to explicitly express them in the risk concept. Probabilities are a good example; these are often applied despite adopting a (C, U) definition. It is important to distinguish between risk as a concept and the process of describing risk; e.g. by using different risk measures or matrices. See 3.4, refer also to risk literature e.g. Aven (2010), for more on this distinction.

3.1 Time of events leading to possible consequences

For the activity or situation considered, for example natural hazards, the concept of risk links to possible initiating or critical events that could happen at some time in the future, which are interlinked to the possible consequences (effects). Time is naturally a key here, as the risk is obviously constrained by the time window considered, which influences the probability of the initiating event. Yang and Haugen (2015) refer to the exposure time influence with more specific labels by referring to e.g. ‘period risk’ and ‘time-dependant action risk’. The main issue is whether some event will occur during the specified period.

In some situations, a specific period is addressed, in which the uncertainty related to the occurrence of the event is somewhat higher. The period is often labelled the ‘risk window’ or ‘exposure risk window’. Fang et al. (2017), in a biomedical context, define ‘risk window’ as “*an interval for the covariate where the risk of adverse event is elevated*”. Furthermore, van Staa et al. (1994), in a study of time window effects in clinical epidemiological studies, show how the choice of the (exposure) risk window can influence risk comparisons. This is because of a risk level varying over time. Depending on the time periods monitored, exposure could be very different. Consider, for example, the risk of aircraft failure during commercial flights. The exposure and probability of failure during take-off and landing is often assumed to be significantly higher, compared with the time between, meaning that the risk is likely to change, depending on the period (risk window) considered.

For the period considered, particularly when dealing with equipment, a focus of risk description is on whether and when the adverse events will occur. The ‘Time at Risk’ (TaR) is an example of a risk measure that gives the duration of time in which the system is functioning, i.e. the time to failure (see e.g. George 2005).

Similarly, there is wide consensus that the concept of reliability (e.g. related to people or equipment) is defined as the “*ability of the item to perform a required function under given conditions for a given time interval*” (ISO 14224:2016). Such ability is usually measured using probabilities. As for risk, the reliability is constrained by the time interval considered. Changing the time interval considered, will, as for risk, usually also change the reliability, making the time element a key to the definition of 'reliability'. Without this element, it could be questioned whether it would lack the required specificity. However, this specificity is not needed for the exposure time when addressing the concept of risk, as the concept is conditional on the activity or situation considered, including the exposure time. For example, walking fast through a mine compared with walking slowly, could produce different risk descriptions, where the exposure is reflected, but as a concept, the focus is on the consequence side, on what could be the consequences and how likely these are. Thus the process leading to the initial event is not explicitly part of the risk concept definition.

3.2 Time of the consequence events

When dealing with risk, which by definition is not deterministic, the possible future outcomes are somewhat building on what we assume as possible at present time. We have some basic knowledge about what will happen in the future, in some situations more than others, but these are all basically predications of possible futures based on how we assume the context will be. Capturing future time is in principle challenging, as the future social context, and timescapes to use Adam's terminology, are following a non-linear relationship and are difficult to predict (Adam 1998). Especially when we try to look far into the future.

The second aspect of the time aspect list (point b) relates specifically to the consequences, which is perhaps the most challenging aspect, as it is strongly interlinked with the element of uncertainty: i.e. what will occur given the activity or situation defined. This is reflected in the current broad set of risk definitions; for example, as already mentioned, risk can be defined as a combination (C, U); see e.g. Committee on Foundations of Risk Analysis (2015) and Aven (2015), ISO 31000:2018 and ISO Guide 73:2009 link uncertainties and the objectives threatened, while the ISO/IEC Guide 51:2014 also addresses the possibility of avoiding or limiting the effects of some hazardous events. There are also standards adopting the definition of risk as a combination of consequences and probabilities (see e.g. ISO 20815:2018). However, from neither is it obvious how the uncertainty relates to the time aspects of such effects of the expected losses (Willis 2007).

Simplified, there are two scenarios of risk with respect to the consequence aspect:

1. Immediate (simple) effects
2. Delayed (complex) effects

In the first scenario, the consequences are revealed directly after or directly because of the initiating events, i.e. simple cause-effect relationships: for example, in gambling, when the game is over and the outcome (loss or winnings) is immediately revealed, or the case of specific equipment failures leading to a specific production downtime. Consider, for example, a car accident; the accident may lead to material damage and loss of lives. In this type of scenario, it is usually a simple task to specify the time of the consequences. The key time aspect of relevance is then the durations influencing the severity of the consequences (e.g. the duration of a fire and the time before emergency response personnel arrived at the site), as would then normally be the aspect linked to the 'uncertainty – consequence' combination. Hence, the duration of the consequence is sufficiently reflected in the risk concept by the current 'consequence' element.

For the second scenario, there are uncertainties related to the occurrences following the initiating event, complicating the task of specifying what is captured by the consequences. These uncertainties could also be of a scientific character. An example is the risk of major nuclear accidents. Consider, for example, the Chernobyl nuclear disaster in 1986. From the aftermath, it is clear the explosion caused radioactive material to precipitate, consequently leading to several fatalities. For this disaster, depending on time perspective, the number of fatalities (consequences) may vary significantly and clearly be subject to dispute amongst experts. Similarly, for the risk of leaking sensitive information and what effects that could have, the consequences could be very different, depending on the period and chain of consequence events considered; reputational issues as one example.

Meaning that the time frame aspect linked to the reliability definition, for the consequence events, should be highly relevant. And, should thus not be ignored.

The time of consequences could to some extent, as indicated in the Introduction, be captured by the consequence events C if these are clearly expressed as conditional on the time considered. It would mean that e.g. 'the computer explodes tomorrow' and 'the computer explodes five years from now' are presented as two distinct consequences. Nevertheless, this way may be conceptually challenged, as it is far from clear that the time *must* be part reading current definitions. Focus is on what will happen, not when. Although it makes perfect sense to include the time, it is not required from the current definition. Clearly leaving it out of the concept can have a strong impact on the way risk is described. On the other hand, it could be difficult to describe this element, which could be a reason for why it is often ignored in practise.

Another way is to include time in the consequences is by performing temporal discounting. It is another and economics-based approach for dealing with the same consequence occurring at different times. Then a consequence occurring five years from now can easily be compared with consequences of tomorrow by adjusting for the temporal effect using a discounting rate. The consequences expressed then reflects also the time aspect, at least for consequences that can be expressed by monetary values. However, the argument is similar as above; this is not required from the definitions. Besides, one could argue that even though one discount for the temporal effects, the time of the consequences matter for other reasons, and should be explicitly part of the risk concept.

For both scenarios, both the immediate and delayed effects, the concept of risk (as currently defined) includes the time aspect post initial events by implicitly integrating these in the 'consequence' element and could, thus, theoretically include everything occurring as a result of the initial event. A simple way to handle this in description of risk is by categorizing into e.g. short- and long-term consequences, as these will present different relevant dimensions. In practice, it is then left to the framing of the situation, including the specification of the consequence period, as to what are the relevant consequences, meaning that, in any case, the consequences could be seen as dependent on the period considered. It is relevant to include the time consequences occur, but not the duration, which is already covered.

3.3 Time of the system framing

The time of the framing (point c in the list above) relates particularly to the human resource situation. This strongly influences the framing of the assessment, including the strength of knowledge, as the available information may change over time and could obviously produce different risk results due to changing conditions, activities, environment, etc. As Haimes (2016, p. 54) points out, the time frame plays a significant role in risk assessment: "*Since the present is deterministic, and the future is not, there is an imperative need to assess the future states of the system as they might respond and evolve as a consequence of emergent forced changes. Thus, the criticality of the time frame in risk analysis and in understanding and assessing the evolving states of the system over time*".

The changing frame makes it important to select appropriate methods that can address time-dependent effects in risk assessments. For example, Barua et al. (2016) propose a risk assessment methodology for dynamic systems based on a Bayesian network, which represents the dependencies among variables graphically and captures the changes of variables over time by the dynamic Bayesian network. Refer also to an extensive review of dynamic risk assessment approaches applicable to the chemical process industries in Villa et al. (2016), where several improvements are traced to the increasing use of real-time monitoring in process facilities, which allows for a sort of 'live' monitoring or picturing of the risk.

The need to capture the changing frame splits into the three different time notions discussed in Yang et al. (2018):

- Operational risk assessment
- Dynamic risk assessment
- Real-time risk assessment

Operational risk management is focused on the decision-making being informed with the relevant risk information available, whereas, for dynamic risk assessment, the focus is more on models and analysis with frequent updating, and, for real-time risk assessment, the focus is on using real-time data to update the risk analysis. All three notions address timing and suggest that it matters when this is performed, due to possibly changing conditions and influences conditioned on time, but from a risk description activity, and not for the risk concept per se.

Furthermore, the timing aspect is particularly evident for the assessment and understanding of emerging risks, related to the effects of new technologies, societal and environmental changes, changing the system and possibly bringing along new or unforeseen threats with the potential for significant consequences. See, e.g., the discussion on industrial accidents triggered by natural hazards in Krausmann et al. (2011). The risks may seem small, based on the current knowledge, as one might not until later recognize the potential for significant consequences, as, for example, was highly evident in the aftermath of the Fukushima Daiichi nuclear disaster in 2011. When expressing risk at a specific point in time, the uncertainty then reflects the frame conditions at that time. For this nuclear facility, the design of the Fukushima reactors met the regulatory requirements, and it was believed that the protective measures, in the case of earthquakes, were robust and adequate (Hollnagel and Fujita 2013). Generally, the risk is conditioned on the frame at a specific point in time. For a different point in time, the knowledge could change, and the risk could thus be different, which is a motivation for adopting a dynamic approach. Nevertheless, the aspect of when the assessment is performed is a matter of what knowledge is available for the risk description, which is captured by the uncertainty (or probability) element in combination with the possible consequences. Adding an element on the time of the assessment into the risk concept definition, is in our view not making any sense.

3.4 More on the link to description of risk

As already mentioned, and expressed in ISO 31000:2018, the concept of risk should be understood distinct from the characterization of risk, i.e. how to describe, estimate or express the risk; see also Aven (2010). However, the characterization provides strong indication and insights as to which attributes of risk are of interest, which relates to the conceptualization of risk.

When addressing various risk measures applied within the area of risk analysis, for example those listed in Table 1 selected from population characterized in Johansen and Rausand (2012), it is clear that time is represented in many of them, indicating the relevance of capturing the element of time particularly in relation to the consequences. Although not all, a large fraction of the measures used in consequence estimation is given as a function of time. Such estimation covers a wide range of consequences such as production loss, human health loss, assets loss, and environmental losses (Khan and Haddara 2004).

Mathematical models capturing the time aspect could be applied for the estimation. A presentation of different approaches is provided in e.g. Cozzani and Salzano (2004) and Arunraj and Maiti (2009).

There are also several risk measures having no specification of time at all but still implicitly relating to the period considered, such as various frequency measures, e.g. the 'frequency of intermediate events', being the frequency of hazardous or intermediate events in an accident scenario (NORSOK Z-013:2010). However, the calculation of the frequencies is normally made under the assumption of a constant rate, with the aspect of time being clearly involved.

4. Temporal inclusion - Recommendations on how to define and express the concept of risk

The argumentation in the previous section shows that several aspects of time are integrated into the risk concept but not explicitly captured by common definitions. There appears to be a lack of specificity to the current risk definitions, suggesting a concept in which time is ignorable, which should not be the case, as the element of time could be important to the understanding of risk.

A way to adjust for this discrepancy is to address 'time' in a similar way to that for the concept of reliability: i.e. that it specifies events occurring "…*for a given time interval*". This could extend the risk concept by capturing relevant periods (time frame) considered, i.e. being strictly the effects (consequence) side of the bow tie, as outlined in Section 3.2. This broader interpretation would then more explicitly capture the range of what can occur and when. But, it should not capture the time influence on exposure window or on knowledge for risk assessments, as also concluded in 3.1 and 3.3. Exposure window is given by the framing of the situation or activity considered; for example the risk of walking through a mine. Further, the uncertainty (U) element sufficiently captures the time of the assessment and is already included, and, duration of the consequence is captured by the consequence (C) element.

Overall, the suggested definition is then an extension of the (C, U) alternative, appropriately expressed as a combination of consequences, uncertainties and time, denoted as (C, T, U), where each of the three elements is interlinked. The T refers to the time of the consequences, which is clearly uncertain.

The proposed definition builds on the idea that the time frame influences both the possible causes and consequences of an activity, as well as the associated uncertainties, but where only the effect on the consequences needs to be expressed by the concept definition. Hence, the T element is included in the definition, where the risk of an activity or situation is more appropriately defined as;

the combination of the possible consequences, the time when these occur, and the associated uncertainties.

In expressing risk in analysis, all three elements should then be included somehow. An illustrative example is provided in the section below.

5. Example – Discussion on the implications of the recommended definition

As a basis for discussing the rationale for the proposed definition of risk, let us consider a simple example, where we consider the risk of a 200 thousand-ton acute crude oil spill to the sea. To see the implications of the recommended definition of risk, we first look into how risk can be described if the risk is defined as the combination of consequences and associated uncertainties.

The crude oil spill to the sea is denoted as A, while the consequences of A are denoted as C. There is uncertainty about the consequences of the crude oil spill. How likely it is that a specific C will have different outcomes can be expressed by probabilities. We may, for example, assign a probability of 10% that the consequences are three times higher than the calculated average value: z. This probability value is set with reference to some background knowledge, K. In mathematical terms, this is written as $P(C>z|K) = 0.10$.

As argued in this paper, the element of time is central to the understanding of risk and contributes to a more specific description of risk. This is clarified in the following.

First, when framing the situation, it is insufficient to define the accidental event A without focusing on the time dimension. This follows directly from the fact that the consequences and the associated uncertainties are not only dependent on the size of the crude oil spill to the sea. The consequences can, for example, be very different, depending on whether the crude oil spill occurs over one day or during the period of one year. With no clarification of the time line, when describing the event A, we are not able to adequately describe the consequences and the associated uncertainties. Meaning we are not able to describe the risk. Such framing could also be performed from a (C, U) perspective, although the focus on time being less stringent.

Second, and the main effect of adopting a (C, T, U) perspective, is that the consequences of an oil spill cannot be predicted properly without referring to the time dimension. There are different ways to this for risk description, but conceptually the key is simply to include it somehow. We may, for example, predict that a specific crude oil spill to the sea may reduce the fish stock by 20% for the year considered. The immediate consequences of the crude oil spill, for this one year, could be a reduction in the fish stock equal to 20%, while the consequences can be very limited, if we consider the consequences five years after the oil spill occurs, as the fish stock may have a strong ability to recover to the same level as before the damage (low recovery time).

It also follows that the uncertainties is affected by time. The uncertainties can, for example, be considered as high, if attention is given to the consequences of the crude oil spill at present, while the uncertainty could be very low, if attention is on what the consequences are five years after the oil spill occurs. This latter will be the case if the recovery time for the crude oil spill is less than five years.

Our main message is that, without clarifications of the time dimension, we cannot accurately describe the accidental event, we cannot properly predict the consequences and we cannot give a proper assessment of the uncertainties. We are not able to clearly understand nor describe the risk.

In the discussion on the importance of time, we may also add that the prediction of the consequences of an accidental event is often made under the assumption that the accidental event occurs in the present. It could also be of interest to focus on the risk if the accidental event occurs in the future. What, for example, is the risk of this crude oil spill if it occurs in 2045? The world is constantly changing, and the consequences could be significantly different, depending on whether it occurs at the present or in the future. This type of consideration can be of importance for long-term projects, since environmental goods change over time, while technological progress can change future costs.

From the example above, we see that time is an important dimension to include in order to give a clear description of risk. One may of course argue that, even for a definition of risk as a concept without reflecting upon the time dimension, one will still cover this dimension, as one needs to incorporate it in order to be precise on what is the meaning of the accidental event, the consequences and the associated uncertainties and, thereby, also the risk. Our main message is, however, that, when one needs to take the time dimension into consideration to get a clear description of risk, it should be explicitly and not only implicitly incorporated in the definition of risk.

6. Concluding remarks

Risk is about what might happen in the future. To capture this, a two-dimensional definition of risk as a C, U combination is extended with the element of T for the time of the consequences.

Regardless of whether a (C, U) or a (C, P) perspective is adopted, the element of time would influence the understanding of risk. While it is clearly possible using the current risk concepts to express risk in way that captures time of consequences, this is not at all required from the definitions. For example, losing 1000 euros today or losing the same amount someday next month, could be regarded as the same consequence based on current definitions. This time aspect could be more precisely expressed in many practical applications, however that is not our focus here; the point is that it may have a significant impact on the results we arrive at. But, it is not a matter of whether it is difficult to achieve or not. Defining it in such a way forces the risk analyst to include an evaluation on when the consequences will occur. Now this could have been done anyway in risk description, by for example listing consequences happening at different times as different consequences or with temporal discounting. These are valid ways, which captures time, but is then done in accordance to both the current risk perspective as well as the (C, T, U) perspective. It is similar to the argumentation for adopting a risk perspective including uncertainties U instead of probabilities p; it is possibly to express a broader uncertainty picture in both, but not required.

A key motivation for adopting the revised definition, is the ruling definition of reliability (given in the last paragraph of 3.1). It is commonly recognized that reliability as a concept, which is a concept closely related to risk, should specify the aspect of time. Reliability of an item is interlinked with the frame considered and cannot be studied without specifying the relevant time. In the same way, risk should also be specified with reference to the time is considered.

Clearly, there are time aspects already covered by the current definitions, making it unnecessary to capture time of risk assessment, exposure time or duration of consequences in the conceptual definition. The aspects are highly relevant for how risk is expressed, but is already part of the (C, U) perspective definition. However, the time of the consequences, T, providing insights into the period in focus, should also be added to the definition. This is achieved from the suggested definition.

In the current article, out focus has been on the concept of risk, and why it is appropriate to include the time element T explicitly. Although we have referred to the assessment phase and listed different risk description measures, we have provided limited discussion on what the effect is on risk description. Further discussion and studies are advised to identify appropriate ways to apply the definition and capture the T element in risk analysis.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

1. Adam, B. 1998. Timescapes of Modernity: The Environment and Invisible Hazards. London: Routledge.

2. Adam, B. 2008. The timescapes challenge: Engagement with the invisible temporal. In: Adam B., Hockey J., and Thompson P., Edwards R. (Ed.): *Researching Lives Through Time: Time, Generation and Life Stories. Timescapes*. Working Paper Series No.1. University of Leeds.
3. Arunraj, N.S., Maiti, J. 2009. A methodology for overall consequence modeling in chemical industry. *Journal of Hazardous Materials*, 169: 556-574.
4. Aven, T. 2010. On how to define, understand and describe risk. *Reliability Engineering and System Safety*, 95(6): 623-631.
5. Aven, T. 2011. On the new ISO guide on risk management terminology. *Reliability Engineering and System Safety*, 96: 719-726.
6. Aven, T. 2015. *Risk Analysis*. Second edition. Chichester, UK: John Wiley & Sons, Ltd.
7. Ball, D., Floyd, P. 1998. Societal Risk. Report prepared for the Health and Safety Executive; London, UK: HSE Books.
8. Barua, S., Gao, X., Pasman, H. and Mannan, M.S. 2016. Bayesian network based dynamic operational risk assessment. *Journal of Loss Prevention in the Process Industries*, 41: 399-410.
9. Bohnenblust, H., Slovic, P. 1998. Integrating technical analysis and public values in risk-based decision making. *Reliability Engineering and System Safety*, 59: 151-159.
10. Committee on Foundations of Risk Analysis. 2015. Society for Risk Analysis Glossary. June 22 version. In: http://www.sra.org/sites/default/files/pdf/SRA_glossary_20150622.pdf
11. Cox, Jr, T.A. 2002. *Risk Analysis – Foundations, Models and Methods*. Norwell, MA, USA: Kluwer Academic Publishers.
12. Cozzani, V., Salzano, E. 2004. The quantitative assessment of domino effects caused by overpressure. Part I. Probit models. *Journal of Hazardous Materials*, 107: 67-80.
13. Fang, T., Mackillop, W., Jiang, W., Hildesheim, A., Wacholder, S. and Chen, B.E. 2017. Bayesian method for risk window estimation with application to HPV vaccine trial. *Computational Statistics & Data Analysis*, 112 (August): 53-62.
14. George, M. 2005. Identification of time at risk periods of significance to ALARP justifications. In: Redmill F., Anderson T. (eds) *Constituents of Modern System-safety Thinking*. London: Springer.
15. Haimes, Y.Y. 2016. *Risk Modeling, Assessment, and Management*. Fourth edition. Hoboken, NJ, USA: John Wiley & Sons, Inc.
16. Hollnagel, E., Fujita, Y. 2013. The Fukushima disaster - Systemic failures as the lack of resilience. *Nuclear Engineering and Technology*, 45(1): 13-20.
17. ISO 9000:2015. Quality management systems — Fundamentals and vocabulary.
18. ISO 14224:2016. *Petroleum, petrochemical and natural gas industries — Collection and exchange of reliability and maintenance data for equipment*. Third edition.
19. ISO 20815:2018. *Petroleum, petrochemical and natural gas industries — Production assurance and reliability management*. Second edition.
20. ISO 30400:2016. Human resource management — Vocabulary.
21. ISO 31000:2018. *Risk management — Guidelines*. Second edition.
22. ISO Guide 73:2009. *Risk management — Vocabulary*. First edition.
23. ISO/IEC Guide 51:2014. *Safety aspects — Guidelines for their inclusion in standards*. Third edition.
24. Johansen, I.L., Rausand, M. 2012. Risk metrics: interpretation and choice. In*: Proceeding of the IEEE International Conference on Industrial Engineering and Engineering Management*, pp. 1914-1918.
25. Jonkman, S.N., van Gelder, P.H.A.J.M. and Vrijling, J.K. 2003. An overview of quantitative risk measures for loss of life and economic damage. *Journal of Hazardous Materials*, 99: 1-30.
26. Khan, F., Haddara, M.R. 2004. Risk-based maintenance (RBM): a new approach for process plant inspection and maintenance. *Process Safety Progress*, 23: 252-265.
27. Krausmann, E., Cozzani, V., Salzano, E. and Renni, E. 2011. Industrial accidents triggered by natural hazards: an emerging risk issue. *Natural Hazards and Earth System Sciences*, 11: 921-929.
28. LUL - London Underground Limited. 2001. LUL QRA – London Underground Limited quantitative risk assessment. Update 2001, Issue 1, June 2001. London, UK: LUL.
29. NORSOK Z-013:2010. *Risk and emergency preparedness assessment*. Third edition, October. Standards Norway.

30. Paltrinieri, N., Scarponia, G.E., Khan, F. and Hauge, S. 2014. Addressing Dynamic Risk in the Petroleum Industry by Means of Innovative Analysis Solutions. *Chemical Engineering Transactions*, 36: 451-456.
31. Purdy, G. 2010. ISO 31000:2009—Setting a new standard for risk management. *Risk Analysis*, 30(6): 881-886.
32. van Staa, T.P., Abenhaim, L. and Leufkens, H.A. 1994. Study of the effects of exposure misclassification due to the time-window design in pharmacoepidemiologic studies. *Journal of Clinical Epidemiology*, Feb; 47(2): 183-9.
33. Villa, V., Paltrinieri, N., Khan, F. and Cozzani, V. 2016. Towards dynamic risk analysis: a review of the risk assessment approach and its limitations in the chemical industry. *Safety Science*, 89: 77-93.
34. Willis, H.H. 2007. Guiding resource allocations based on terrorism risk. *Risk Analysis*, 27: 597-606.
35. Yang X. et al. 2018. Clarifying the concept of operational risk assessment in the oil and gas industry. *Safety Science*, 108: 259-268.
36. Yang, X. and Haugen, S. 2015.Classification of risk to support decision-making in hazardous processes. *Safety Science*, 80: 115-126.
37. Zio, E. 2018. The future of risk assessment. *Reliability Engineering and System Safety*, 177(C): 176-190.

Table 1 Overview of risk measures involving an element of time (selection)

	Metric name and reference	**Description**	**Time aspect**	
			Exposure risk window	**Time of the consequences**
1.	EL - Expected economic loss (Jonkman et al. 2003)	Expected value of economic loss per year.		X
2.	FAR - Fatal accident rate (NORSOK Z-013:2010)	Expected number of fatalities within a specific population per 100 million hours of exposure.	X	
3.	IRPA - Individual risk per annum (NORSOK Z-013:2010)	Probability that a specific or hypothetical individual will be killed due to exposure to hazards or activities during a period of one year.	X	X
4.	LIRA - Localized individual risk (Jonkman et al. 2003)	Probability that an average unprotected person, permanently present at a specified location, is killed during a period of one year due to hazardous event at an installation.		X
5.	MCR - Monetary collective risk (Bohnenblust and Slovic 1998)	Expected total loss in terms of monetary units per year, aggregated and weighed across different damage categories (e.g. fatalities, injuries, disruption of service).		X
6.	PEF - Potential equivalent fatality (LUL 2001)	Expected harm per year from both fatalities and injuries, where injuries are expressed as fractions of a fatality.		X
7.	PLL – Potential loss of life (NORSOK Z-013:2010)	Expected loss of fatalities within a specific population per year.		X
8.	SRI - Scaled risk integral (Ball and Floyd 1998)	Group risk per area per year.	X	X