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System of systems perspective on risk: towards a unified concept

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Abstract: Many systems and projects that concern systems engineers, engineering managers, and business managers today can be defined as system of systems (SoS), which are described as ambiguous, uncertain and dynamic, among others. In addition to the traditional view on risk identification, analysis and management, the concept of risk should be considered with respect to these systems of systems. The purpose of this paper is to analyse both fundamental concepts and recent publications in system of systems, business and engineering management, as well as risk analysis, modelling, and management for the purpose of better describing the concept of risk with respect to system of systems. The ultimate goal is to provide engineering and business managers the necessary perspective on the concept of risk and its management for the next generation of systems – including various descriptions of risk and discussion of the relevance of properties of system of systems to sustainable management of risks in engineered systems. To achieve a truly sustainable management of risk, there has to be a change in paradigm from a traditional description of risk to that of a more holistic perspective.

Keywords: risk; uncertainty; complexity; systems approach; system of systems; SoS; system of systems engineering.

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Ipek Bozkurt is an Assistant Professor in both the Engineering Management and Systems Engineering Programmes at University of Houston Clear Lake. She received her PhD and Masters in Engineering Management from Old Dominion University. Her main research areas include personality profiles, agent-based modelling and simulation, complex systems, leadership theories, organisational behaviour, online learning and education, and engineering management and systems engineering.

1 Introduction

It has been argued that the concept of risk is very much related to the concept of undesirable events and consequences and that the apparent differences in use of the word risk can be attributed to the description of desirability (Pinto et al., 2010). This paper builds on this by emphasising the importance of recognising characteristics of systems of systems and complexity for a truly unified concept of risk that towards a unified concept transcends traditional notions. There is indeed little consensus on the definition of risk. However, this lack of consensus is not at all surprising from a systems analysis perspective. This lack of apparent consensus is in fact a property consistent with an abstract concept such as risk in modern-day complex and evolving society wherein human activities are contextualised.

Risk analysis by engineering management and systems engineering/engineers (EMSE) is not new. In 1998, Price (2008) suggested a fairly simplified risk assessment approach composed of two major stages:

- 1 determination of event sequences

2 evaluation of event frequencies and probabilities.

This approach primarily pertains to industrial settings. Other applications of risk assessment in EMSE are discussed by [Componation et al. \(2001\)](#) and by [Weiss and Anderson \(2004\)](#) in organisational effectiveness, by [Carbone and Tippet \(2004\)](#), [Wilhite and Lord \(2006\)](#), and [Parsons \(2007\)](#) in project management and by [Dillon and Tinsley \(2005\)](#) in decision-making.

More recently, there have been attempts to unify various concepts of risk, namely the works of [Aven et al. \(2004\)](#), [Holton \(2004\)](#), and [Samson et al. \(2009\)](#). There are also works of [Letens et al. \(2008\)](#) and [Haimes \(2009\)](#). These works typically describe the various commonly-held definitions of risks, related concepts such as uncertainty and probability, as well as approaches to unify, or at least organise these concepts in a coherent manner. However, none of these works addresses the variations in the definition of risk from a truly systems perspective that capture peculiar characteristics of complex systems. Table 1 shows the usual categorisation of risk based on its type, the data from which it is deduced and the estimation approach.

Table 1 Types of risks and contextual factors

<i>Types of risks</i>	<i>Data type</i>	<i>Estimation approach</i>
<ul style="list-style-type: none"> • Financial • Insurance • Operational • Strategic • ...etc. 	<ul style="list-style-type: none"> • Subjective • Objective 	<ul style="list-style-type: none"> • Deterministic • Non-deterministic

Source: Adapted from [Segal \(2007\)](#)

EMSEs, in their role in “planning, organizing, allocating resources, and directing and controlling activities which have a technological component” ([ASEM, 2010](#)) have to deal with some form of risk management activities. Their “interdisciplinary approach and means to enable the realization of successful systems” [[INCOSE, \(2004\)](#), p.12] are also in this same predicament. However, unlike traditional engineering practitioners, EMSEs are bound to cross-traditional disciplines and will have to deal with whatever difference there may be among these disciplines.

The main purpose of the following sections is to better describe the concept of risk in recognition of emergence and complexity which characterises many systems within the concern of engineering and business managers. The systems that EMSEs deal with today can be considered as system of systems (SoS). These meta complex systems, as described by [Keating et al. \(2003\)](#) are formed by subsystems which are complex systems by themselves. In today’s dynamic and global environment, it is almost impossible to keep up with the ever-changing conditions of businesses, no matter what the industry is. The dynamics of any situation are dependent on both the technological and the social aspects of the context. As [Sauser and Boardman \(2008\)](#) have stated, developing systems to solve complex engineering problems is the most complex and challenging aspect of a project. For EMSEs to identify, analyse and manage risk within these complex systems, there is a need to analyse and discuss risk with respect to SoS.

2 Risk and SoS

To conduct efficient and effective identification, analysis and management of risk, the characteristics of both the event and the system it acts upon need to be defined adequately. An effort difficult in itself, this creates even a bigger problem when dealing with SoS or the derivatives (complex systems, federation of systems, enterprise systems, etc.). As described by Sousa-Poza et al. (2008), one of the ontological conditions for SoS is complexity and uncertainty. Uncertainty, as a foundation of risk, is discussed further in latter stages of this paper. Complexity has various components and definitions, all of which are applicable to SoS. According to Biggiero (2001), an object is complex because it cannot be predicted, either because of logical impossibilities or insufficient computational powers. The amount of information required to describe a system, as well as interdependencies between different parts are considered by Bar-Yam (1993) in his definition of complexity. Other attributes of complexity that are relevant for risk management include lack of holistic perspective (Jackson, 2006), severity and resource availability (Hood et al., 1993), ambiguity (Funke, 1991), stability (Quesada et al., 2005) and time-sensitivity (Augier et al., 2001).

When engineering traditional systems, the tools and methodologies available are sufficient to provide a solution to a defined problem; the analysis conducted is dominated by technological components; and scoping and framing the problem is easy, since the boundaries are fixed. However, when dealing with SoS, the boundaries become fluid, there is no one right way of dealing with the problem at hand since it is emergent, and engineering these systems of systems becomes a *satisficing* issue, rather than *optimising* (Keating et al., 2003). The discussion of risk within the SoS context, therefore, becomes more important and difficult at the same time.

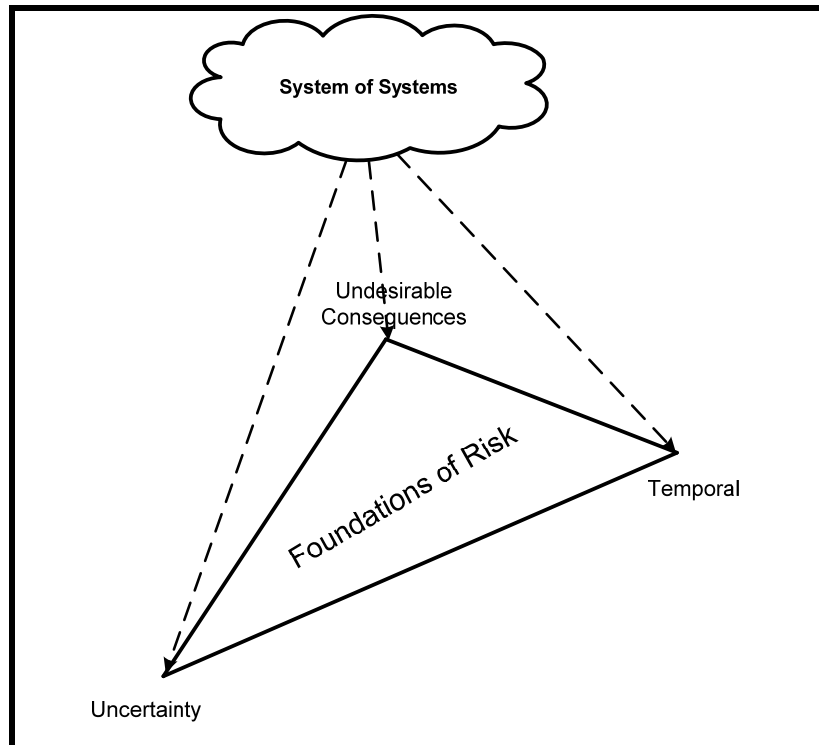
Many studies have been conducted that try to tackle this subject. When discussing models for risk management within SoS, Haimés (2008) also states that risk and uncertainty are ‘unavoidable conditions’ for engineering systems, and single-model analysis and interpretation is not sufficient when dealing with systems with multiple and conflicting objectives. He further states that assessing and managing risk should be a part of the decision-making process within the lifecycle of SoS. Ghadge et al. (2010) take a SoS approach in order to analyse risk within aerospace supply chains. They use this framework to support their discussion of identifying, analysing, evaluating and mitigating risk. Research conducted by Aitken et al. (2010) shows that a process of dynamic risk assessment is an important component when trying to achieve safety in SoS.

Looking at factors shaping the risks faced by critical infrastructures, which are highly integrated systems of interdependent systems, Kroger (2008) uses *societal*, *system-related*, *technological*, *natural* and *institutional* factors. In order to face the challenging tasks put forward by critical infrastructures, he introduces the concept of *risk governance*, where all stakeholders, rules, processes and procedures related to collection, analysis, communication and management of information and decision-making are considered within good governance practices. Baiardi and Telmon (2008) have also looked at critical infrastructures, with a focus on information infrastructure, and provided a mathematical framework for managing risk, and have demonstrated that the addition of non-redundant sets of countermeasures provides an effective risk mitigation plan.

Figure 1 is a representation of the worldview from which the following discussions are made. Three main foundations of risk that were discussed by Pinto et al. (2010) – *undesirable consequences*, *uncertainty* and *temporal components* – can be better

linked through a SoS perspective, i.e., SoS will be the common thread within the foundations of risk.

Figure 1 Worldview of foundations of risk



2.1 First foundation of risk: undesirable consequences

The notion of undesirable events and their characteristic consequences (from hereon will be referred to as the same) permeates human and public psyche for centuries ([Bernstein, 1996](#)). Ever since humans started recognising the perils of sea voyage and long journeys, and the unpredictable weather, the notion of undesirable consequence has been part of daily lives. During classical antiquity (700 BC to 500 AD), appeasing the gods was the only form of dealing with these consequential events. During the Middle Ages (500 AD to 1300 AD), religion dominated many aspects of life and dealing with undesirable consequences were mostly related to ensuring a good afterlife, not this life. Managing and not simply dealing with undesirable consequences started to emerge as humans started to believe they are free agents and to some extent have self-determination.

Around 500 AD, the Hindu Arabic numeral system was developed in India and migrated to Europe over the centuries to provide a numeral system suitable for calculation as the Renaissance started. During the Renaissance (1300) and Protestant Reformation (1517), mysticism started to yield to science and logic. As intellectuals rediscovered the works of the classical Greek philosophers, people started focusing on understanding how the world works. With theory and experiments at the centre of the

scientific method and more pronounced free-will, the future became no longer totally a matter of chance or god's will.

All this eventually leads to the rise of capitalism: epitome of managing undesirable consequences, where the modern methods of dealing with the unknown start with measurement of odds and probabilities. In 1545, Cardano provided the foundation for calculating odds by making the first serious effort to develop the principles of probability, but not yet the theory of probability as known today. Back then, the principle merely equates probability with the number of favourable outcomes divided by the total number of possible outcomes. Around 1654, Pascal and Fermat laid the fundamental groundwork of probability theory. They solved a problem of how to divide the winnings of an incomplete game posed 200 years earlier by Luca Paccioli where the game is played in rounds until one player has won enough rounds. They have concluded that the division of winnings should not depend on what has happened already, but on what could happen if game had continued until finishing. This means that for the first time, people can forecast the future and make decisions with the help of numbers: a big leap in dealing with future undesirable consequences.

Around 1662, John Graunt applied probability to raw data, which was previously only applied to games of chance. Graunt gathered birth and death information and applied sampling methods and used probabilities in an attempted to estimate average expected ages at death. This ushered key theoretical concepts needed for making decisions under conditions of uncertainty, namely sampling and averages. All these notions would lead to the science of statistical analysis.

In the immediately preceding paragraphs, one may aptly recognise the absence of the word risk. This is an intentional omission to emphasise that the modern day common concept associated with this word may carry with it extraneous meanings. As an example, risk is nowadays often described as a function of consequence and probability, e.g., by [Kaplan \(1997\)](#), among other equally valid alternative descriptions. One then may wonder if there was the concept of risk (detached from the word itself) prior to the development of the concept of probability. To avoid going down the path of tracing back in history where the concept of risk originated, the notion of undesirable consequence is used instead without loss of generality.

The immediately preceding paragraphs also make evident the fundamental notion of undesirable consequence, more fundamental than risk itself. Undesirable consequence can be loosely described as an event, whether in the past, the present, or the future which nominally is supposed to be avoided, and thus the use of the term undesirable. Considering that this undesirable event will have severe consequences and implications, not knowing when this event will occur may create additional negative implications. The constant change within structural and behavioural patterns and conditions within a SoS is defined as *emergence* ([Sousa-Poza et al., 2008](#)). According to [Gorod et al. \(2008\)](#), traditional systems are designed to test foreseen good and bad behaviour; whereas in SoS, emergent behaviour is not restricted to what events can be foreseen. The SoSE management matrix developed by [Gorod et al. \(2008\)](#) includes risk management as one of the conceptual areas, and the way risk management deals with emergence is to verify and validate the achievement of new behaviours. The realisation that current problem scenarios in which EMs and SEs work cannot be aptly described by traditional systems notions has been presented by [Keating et al. \(2003, 2008\)](#) and [Pinto et al. \(2006\)](#). They have explicitly and implicitly described the complexity and emergent behaviour of modern types of systems, e.g., SoS, enterprise systems, and federation of systems. Of

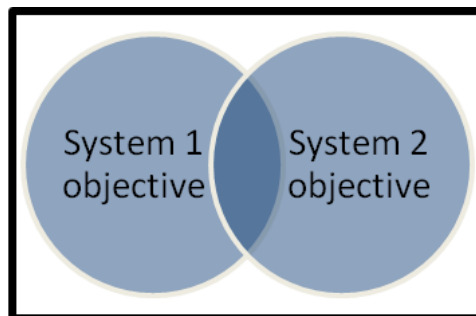
particular interest is the compounding of uncertainty by the emergent behaviour, which cannot be known ahead of time no matter how good the analysis is.

There is an apparent difference in how the word risk is used in various fields of disciplines. The difference is most evident between financial and engineering fields, as pointed out by Poitras (2006). The most apparent difference is that “financial economics associates risk with the possibility that the actual return for a security will differ from the expected return” [Poitras, (2006), p.1]. Nonetheless, it has also been established that these apparent differences in the use of the word risk are problem sensitive [Samson et al., (2009), p.4]. This means that the use of the word risk (and later on, uncertainty) evolved as a result of, or possibly to affect the problems from various fields.

Consider the difference between the expected and actual return of financial securities being termed as risk. Initially, one may deduce that here, risks pertains to both undesirable and desirable consequences. However, upon closer look, one would realise that in financial securities, departure from the expected, whether upside or downside, is undesirable. This is more commonly expressed whenever the concept of volatility is used. This shows that undesirability has more to do with the objective of the individual, the organisation, or the systems, and less with the absolute values of the phenomenon, e.g., high or low returns of financial securities.

As such, herein rests the first foundation of a unified concept of risk for EMs and SEs: that at the most fundamental level, risk is about events that are undesirable based on some notion of recognised objective, i.e., objectives that determine desirable events. As illustrated in Figure 2, for a proponent of a particular system, e.g., system 1, any event that has nothing to do with the systems objective can be undesirable, even if it happens to be an objective of another system, e.g., system 2.

Figure 2 The relationship between system objectives, undesirable events and consequences (see online version for colours)



Source: Adapted from Pinto et al. (2010)

Possibly the most widely held framework in engineering risk analysis is that first presented by Kaplan (1997) and later extended by Haimes et al. (2002). The framework suggests six guiding questions:

- 1st What can go wrong?
- 2nd What are the consequences?
- 3rd What is the chance of occurrence?

4th What can be done to manage them?

5th What are the alternatives?

6th What are the effects on future decisions?

However, recognising that answering the first question is predicated on the recognition of desirable events, i.e., systems objective. As such, being more explicit will result in a precursor question:

0th What are the desirable events?

2.2 *Second foundation of risk: uncertainty*

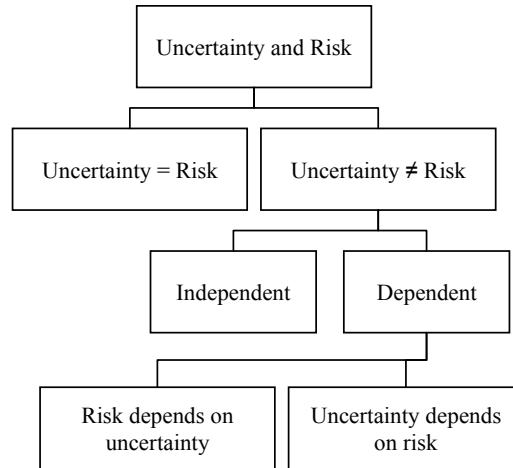
In mathematics, randomness has particular meaning. This is most evident in describing a variable that changes every time it occurs or is observed. It was earlier mentioned that the development of the concept of probability paved the way to more scientific management of undesirable consequence. This was based on the fact that nowadays, probability is often used to represent uncertainty.

In the common language, uncertainty implies doubt, ambiguity, lack of knowledge, and others. It is often useful to further describe sources of uncertainty: aleatory and epistemic. Epistemic uncertainty refers to uncertainty in our state of knowledge about phenomena. This is also known as reducible uncertainty, pertaining to its property to be reduced through investigation, reasoning, and other forms of analyses. Aleatory uncertainty, on the other hand, is due purely to the variation in outcomes of randomness. This is also known as irreducible uncertainty, pertaining to its property of not being reduced by further investigation, reasoning, and other forms of analyses. It should be pointed out that aleatory uncertainty is predicated by the acceptance that randomness truly exists. Uncertainty has been debated for centuries and goes way back to 380 BC as espoused by Plato in his book, the *Republic*, and his cave allegory. His belief was that we can never understand reality empirically. That is, one cannot use our five senses to understand reality.

Jumping forward to the 20th century, a famous attempt to define and distinguish between uncertainty and risk is by Knight (1921) where uncertainty comes in two types: measurable and unmeasurable. With measurable uncertainty, one can come up with a probability to quantify the uncertainty. On the other hand, one cannot even do that for unmeasurable uncertainty. Unmeasurable uncertainty was simply referred to as 'uncertainty' while measurable uncertainty was referred to as 'risk'. So in Knight's perspective, risk is a subset of uncertainty. This was an interesting attempt to distinguish between risk and uncertainty, but it had some peculiarities. For one, it didn't relate the 'consequence of the outcome'. For example, Knight would have considered the roll of dice to be a risk such that one can quantify the probability of the outcome, but will still consider it a risk even if there is no betting involved (Bernstein, 1996).

There is also an apparent difference in the use of the word risk in relation to uncertainty, as discussed by Samson et al. (2009). They essentially described two ways risk and uncertainty are associated:

- 1 whether they pertain to the same concept or different concepts
- 2 whether one depends on the other, as shown in Figure 3.

Figure 3 Conceptual relationships of risk and uncertainty

Source: Adapted from Samson et al. (2009, p.2)

Uncertainty and risk are undoubtedly closely related concepts that both practitioners and academics have struggled to define and distinguish. In fact, Holton (2004) describes an effort by the Society for Risk Analysis (SRA) to define ‘risk’. After four years, the society gave up and concluded that it might be best not to define risk, which inspired Holton to conclude that half the problems result from people using the same words with different meanings, and the other half results from using different words with the same meaning. This society currently defines risk as the “potential for realization of unwanted, adverse consequences to human life, health, property, or the environment” (SRA, 2010). Uncertainty is also a defining characteristic of SoS in terms of boundaries of SoSE problems; that boundaries are flexible as the knowledge about a certain situation is accumulated (Sousa-Poza et al., 2008).

Referring again to Figure 3, current practices in EMSE espouse more the notion that risk is not equal to uncertainty but has a dependency relationship with uncertainty. Exactly which one causes the other is beyond the scope of this paper. Nonetheless, the complex cause-and-effect nature of the problem domain in which EMSEs work lend themselves more towards the notion that risk is caused by uncertainty. Lawrence and Lorsch (1967) developed a scale that characterises uncertainty as follows: lack of clarity of information, general uncertainty of causal relations, and long time span of feedback about results. The first characteristic can be considered as a combination of ambiguity and lack of information. The second characteristic deal with the relationships (causal, in their case) between variables, and the third characteristic is a temporal component. Another scale, devised by Duncan (1972), considered three different issues regarding uncertainty: lack of information regarding factors related to decision-making, lack of knowledge about the implications of an incorrect decision, and how to evaluate the importance of environmental factors on the performance of the organisation.

As such, herein rests the second foundation of a unified concept of risk for EMs and SEs: that at the least, there is some causal relationship between uncertainty and undesirable events. This bears most meaning in the context of choosing among

alternatives, each having its own uncertainty of undesirable results (e.g., decision-making scenario).

2.3 Third foundation of risk: temporal domain

[Hofstetter et al. \(2002\)](#) succinctly analogised the temporal domain in risk analysis by likening risks to the ripples produced by a pebble dropping on a pond. In this analogy, the various types of risks were described as: Target risk – the risk scenario which prompts the whole decision process, often reflected by the main objective; and countervailing risk – the risk that arises from the action of managing the target risk. The notion of countervailing risk clearly emphasises that risks and any present decision to take or not take action may have an effect in the future. In particular, other risks may arise as a result.

[Haimes \(2008\)](#) emphasised the importance of recognising the temporal perspective in characterising the state space of a system. More recently, [Haimes \(2009\)](#) emphasised the importance of temporal domain when looking at risks from a systems perspective. In a great degree, this has already been implied with the last of the six guiding questions. That is, every time an analyst tries to describe the effects of risk management alternatives on future decisions, he or she is bound to consider the temporal dimension of the entire risk analysis and management activity.

Time-dependency of complex systems and complex problems has been addressed by various studies. [Quesada et al. \(2005\)](#) have stated that if a complex problem is time-dependent, it means that decisions must be made at the correct moment in relation to environmental demands. [Augier et al. \(2001\)](#) have argued that the time available to solve the problem is part of problem solving. However, the temporal domain of looking at risk is also the reflection of other properties of SoS, namely tight coupling among its constituent systems, and the lack of complete understanding of its entirety. Tight coupling implies that what occurs in one constituent directly affects what happens in another; that they are dependent on each other.

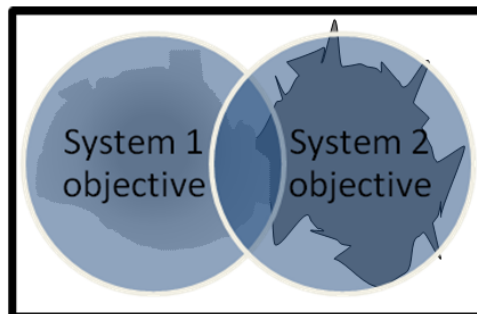
But possibly the most insightful generalisation of the apparent lack of consensus on risk is that of [Hatfield and Hippel \(2002\)](#) when they concluded that risk analysis is predicated on an earlier systems identification. This essentially implies that systems analysis is a critical and precursory task in risk analysis. This generalisation implies the importance of recognising system objectives prior to describing risk, i.e., the need to first describe what desirables are before describing what undesirables are. More recently, this same implication has been made in a much narrower context of anti-goals in software development ([van Lamsweerde, 2009](#)) and in the transference of risk in project integration ([Alali and Pinto, 2009](#)).

As such, herein rests the third foundation of a unified concept of risk for EMSEs: undesirable consequences are time-sensitive. That is, the current declaration of what may be undesirable is a mere snap-shot of an ever-evolving scenario. As shown in Figure 4, events that are held as desirable and undesirable may change through time, in the same way as system objectives evolve and new ones emerge.

This leads a modification to the guiding questions of risk management to explicitly include the temporal domain as follows:

- 0th What are the desirable events at a particular time?
- 1st What can go wrong?
- 2nd What are the consequences?
- 3rd What is the chance of occurrence?
- 4th What can be done to manage them?
- 5th What are the alternatives?
- 6th What are the effects beyond this particular time?

Figure 4 The relationship between system objectives, undesirable events and consequences, and temporal domain (see online version for colours)



Source: Adapted from Pinto et al. (2010)

3 Conclusions

With complex, dynamic environments characterised by ambiguity, uncertainty, and emerging risks, a change in paradigm is required for the sustainable management of risk. At the base of the new paradigm, a holistic description of risk is required to supplant the traditional view. Even though the concepts of undesirable events, uncertainty, and temporal domain have been previously identified as critical towards a unified notion of risk, we advocate an improved view from a SoS perspective. This new perspective provides a better explanation of how the temporal domain is a result of evolution in systems objectives coupled with risk emergence in systems behaviour. We merge our unified notion of risk to supplement the six guiding questions of risk management with a precursor question regarding systems objectives and explicitly frame the question in terms of temporal domain. This brings EMSEs closer to a unified notion of risk necessary to transcend traditional boundaries. The new paradigm of enterprise risk management (ERM) is being advocated in various disciplines as necessary to break down the silos of traditional risk management. This paper is a first step in applying a SoS perspective to the multi-dimensional understanding of risk that will eventually lead to work on applying SoS to the ERM paradigm.

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