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RISK AND SYSTEM-OF-SYSTEMS: TOWARD A UNIFIED CONCEPT

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Abstract
The scope of this paper is the survey of both fundamental and most recent publications in system-of-systems, business and insurance, as well as risk analysis, modeling, and management for the purpose of better describing the concept of risk in recognition of emergence and complexity which characterizes many systems within the concern of engineering and business managers. The ultimate goal is to provide engineering and business managers the necessary perspective on the concept of risk and in its management for the next generation of sustainable 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. The result shows that to address a truly sustainable management of risk, there has to be a change in paradigm from traditional description of risk to that of a more holistic perspective.

Key Words
Risk, uncertainty, complexity, systems approach

Introduction
"Given the ubiquity of risk in almost every human activity, it is surprising how little consensus there is about how to define risk. " - Damodaran (2008, p. 3)

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 of an abstract concept such as risk in modern-day complex and evolving society wherein human activities are contextualized.

Risk analysis in engineering management is not new. In 1998, Price suggested a fairly simplified risk assessment approach composed of two major stages: (1) determination of event sequences, and (2) evaluation of event frequencies and probabilities. This approach primarily pertains to industrial settings. Other well-discussed applications of risk assessment in engineering management are by Componation, et al., (2001), and by Weiss and Anderson (2004) in organizational effectiveness, by Carbone and Tippett (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 concept 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). Many of these works describe very well the various commonly-held definitions of risks, related concepts such as uncertainty and probability, as well as approaches to unify, or at least organize 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. Exhibit 1 shows the usual categorization of risk based on its type, the data from which it is deduced and the estimation approach.

Exhibit 1. Types of risks and contextual factors (adapted from Segal 2007)

Types of Risks	Data volume	Data type	Estimation approach
- Financial - Insurance - Operational - Strategic ... etc.	-High -Low	- Subjective - Objective	- Deterministic - Nondeterministic

Engineering managers, 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. Systems engineers, in 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, EM's and SE's 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 characterizes many systems within the concern of engineering and business managers.

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. Ever since humans started recognizing 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 (500AD to 1300AD), religion dominated many aspects of life and dealing with undesirable consequences were mostly related to ensuring a good afterlife, not this life. However around 500 AD, the development of the Hindu Arabic numeral system provided more suitable calculation. 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.

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 center 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 favorable 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 two hundred 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 recognize the absence of the word *risk*. This is an intentional omission to emphasize 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 to the word itself) prior to the development of the concept of probability. To avoid going into 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.

There is an apparent difference on 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 Potras (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 pp.4). This means that the respective use of the word risk (and later on, uncertainty) evolved as a result of, or possible 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 realize 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 organization, or the systems, and less with the absolute values of the phenomenon, e.g. high or low returns of financial securities.

As such, herein rest the first foundation of unified concept of risk for EM's and SE's: that at the most fundamental level, risk is about events that are undesirable based on some notion of recognized objective, i.e. objectives that determine desirable events.

Second foundation of risk: uncertainty

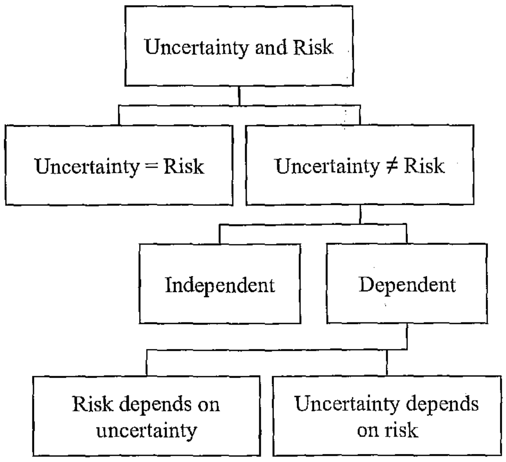
In mathematics, randomness has particular meaning. This is most evident in describing variables that change every time it occurs or is observed. It was earlier mentioned that the development of the concept of probability paved the way to more scientific management of undesirable consequence. This was 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 380BC 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.

There is also an apparent difference on 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) that these two pertains to the same or different concept, and 2) which one depends on the other, as shown in Exhibit 2

Exhibit 2. Conceptual relationships of risk and uncertainty (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 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 of the problems results from people using same words with different meanings, and the other half results from using different words with the same meaning. For completeness, this society currently defines risk as the "potential for realization of unwanted, adverse consequences to human life, health, property, or the environment" SRA (2010).

Referring again to Exhibit 2, current practices in SE's and EM's espouse more the notion that risk is not equal but has a dependency relationship with uncertainty. Exactly which one causes the other is beyond the coverage of this paper. Nonetheless, the complex cause-and-effect nature of the problem domain by which SE's and EM's lend themselves more towards the notion that risk is caused by uncertainty.

As such, herein rest the second foundation of unified concept of risk for EM's and SE's: 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).

Third foundation of risk: Temporal domain

Hofstetter, et al. (2002) succinctly analogized 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 emphasizes 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.

The realization that current problem scenarios in which EM's and SE's work with 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 behavior of modern types of systems, e.g. system of systems, enterprise systems, federation of systems. Of particular interests is how the emergent behavior, which cannot be known ahead of time no matter how good the analysis is, is a way that compounds uncertainty. Haimes (2008) emphasized the importance of recognizing the temporal perspective in characterizing the state space of a system. Possibly the most held framework in engineering risk analysis is that first presented by Kaplan (1997) and later extended by Haimes (2002) into six guiding questions:

What can go wrong?
What are the consequences?
What is the chance of occurrence?
What can be done to manage them?
What are the alternatives?
What are the effects to future decisions?

More recently, Haimes (2008) and Haimes (2009) emphasized 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 to future decisions, he or she is bound to consider the temporal dimension of the entire risk analysis and management activity.

However, the temporal domain of looking at risk is also the reflection of other properties of system of systems, namely tight coupling among its constituent systems, and the mere 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.

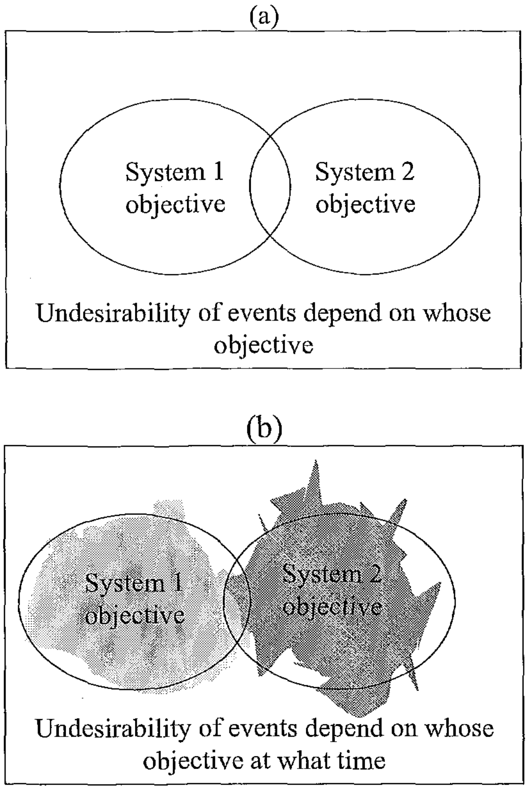
But possibly the most insightful generalization of the apparent lack of consensus on risk was that of Hatfield and Hippel (2002) when they concluded that risk analysis is predicated to an earlier systems identification. This essentially implies that systems analysis is a critical and precursory task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

As such, herein rest the third foundation of unified concept of risk for EM's and SE's: 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.

Conclusion

The concept of risk is strongly hinged on the concept of undesirable events and consequences. The apparent differences in use of the word risk can often be traced back to the fact that what may be desirable from one person, organization, or systems may be undesirable to another. With the financial risk as an example, it is important to emphasize that undesirability has more to do with the recognized objective rather than an absolute value of the event (e.g. volatility in the price versus low or high price of financial securities). Exhibit 3 uses as an analogy the set of points inside the rectangle as all possible events. In Exhibit 3a, the points inside the ovals designate events which are recognized to be objectives of particular systems, i.e. the desirable events can now be differentiated from the undesirable events. The importance of recognizing objectives and their intersection or lack thereof is precursor to any form of risk analysis, assessment or management. Nowadays, EM's and SE's are most frequently relied on do such recognition as part of the systems identification activity.

Exhibit 3. The relationship between system objectives and undesirable events and consequences.



The importance of the notion of uncertainty cannot be overemphasized – both for its own conceptual challenges as well as how it is often used in describing the concept of risk. Of particular importance to EM's and SE's are recognizing possible causes of uncertainties and how to express such uncertainties.

Finally, the complexity of present-day environment in which EM's and SE's works are contextualized adds a temporal domain to what are undesirable events and their corresponding uncertainties. In particular, complexity, emergence, and tight coupling bring about changes to what is believed to be systems objective. As a result, undesirable events also change accordingly. This is shown in Exhibit 3b as non-uniform boundaries between the desired and the undesired events. The temporal domain of undesirable events results to other sequentially related concepts that become entrenched in the ways people describe risk, e.g. opportunity, agility, robustness, vulnerability, threat, etc.

In essence, 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 of an abstract concept such as risk in modern-day complex and evolving society wherein human activities are contextualized. The article shows that to address a truly sustainable management of risk, there has to be a change in paradigm from traditional description of risk to that of a more holistic perspective based on the more fundamental concepts of undesirable events, uncertainty, and temporal domain.

References

Alali, Baqer and C. Ariel Pinto "Project, Systems, and Risk Management Processes & Interaction," *Proceedings of the PICMET '09 Portland International Center for Management of Engineering and Technology*, Portland, Oregon, USA (August 2-6) 2009.

ASEM, American Society for Engineering Management website, <www.asem.org>, cited April 6 (2010).

Aven, Terje, Espen Fyhn Nilsen, Thomas Nilsen "Expressing Economic Risk: Review and Presentation of a Unifying Approach," *Risk Analysis*, 24:4 (2004) pp. 989-1005.

Carbone, Thomas .A. and Donald D Tippett "Project Risk Management Using the Project Risk FMEA," *Engineering Management Journal*, 16:4 (2004) pp. 28-35.

Componation, Paul J, Dawn R. Utley, and James J. Swain "Using risk reduction to measure team performance," *Engineering Management Journal,* 13:4 (2001) pp. 27-34.

Damodaran, Aswath *Strategic Risk Taking: A Framework for Risk Management,* Wharton School Publishing, New Jersey, USA, (2008).

Dillon, Robbin .L. and Catherine H. Tinsley "Interpreting near miss events" *Engineering Management Journal*, 17:4 (2005) pp. 24-30.

Haimes, Yacov Y. "Models for risk management of systems of systems," I*nternational Journal of System of Systems Engineering*, 1:1-2 (2008) pp: 222 – 236.

Haimes, Yacov Y. "On the Complex Definition of Risk: A Systems-Based Approach." *Risk Analysis*, 29:12 (2009) pp. 1647-1654.

Hatfield, Adam J. and Keith W. Hipel "Risk and Systems Theory," *Risk Analysis*, 22:6 (2002) pp. 1043-1057.

Hofstetter, Patrick, Jane C. Bare, James K. Hammitt, Patricia A. Murphy, and Glenn E. Rice, "Tools for Comparative Analysis of Alternatives: Competing or Complementary Perspectives?," *Risk Analysis*, 22:5 (2002) pp. 833-851.

Holton, Glyn .A. "Defining Risk," *Financial Analysts Journal*, 60:6 (2004) pp. 19-25.

INCOSE, Systems Engineering Handbook, INCOSE-TP-2003-016-02, Version 2a, 1 June (2004).

Kaplan, Stan "The Words of Risk Analysis," *Risk Analysis*, 17:4 (1997). pp. 407-417

Keating, Charles., Ralph Rogers., Resit Unal, David Dryer, Andres Sousa-Poza, Robert Safford, William Peterson, and Ghaith Rabadi,. "System of Systems Engineering," *Engineering Management Journal*, 15:3. (2003) pp. 36-45.

Keating, Charles., Andres Sousa-Poza, and Samuel Kovacic, "System of Systems Engineering: An Emerging Multidiscipline," *Int. J. System of Systems Engineering*, 1:1/2, (2008). pp. 1-17.

Knight, Frank H. *Risk, Uncertainty, and Profit*. Boston, MA: Hart, Schaffner & Marx; Houghton Mifflin Company, (1921).

Letens Geert L., Lieve Van Nuffel, Aimee. Heene. Jan Leysen, "Towards A Balanced Approach In Risk Identification," *Engineering Management Journal* 20:3 (2008) pp. 3-9.

Parsons, Vickie. S. "Searching for "Unknown Unknowns" *Engineering Management Journal,* 19:1 (2007) pp. 43-46.

Price, John W.H. "Simplified risk assessment," *Engineering Management Journal*, 10:1 (2008) pp. 19 – 23.

Samson, Sundeep, James A. Reneke, Margaret M. Wiecek, "A review of different perspectives on uncertainty and risk and an alternative modeling paradigm," *Reliability Engineering & System Safety*, 94:2, (2009) pp. 558-567.

Segal, Sim, "Defining Risk Appetite" Presentation at the *ERM Symposium*, Chicago, Illinois, March 29, (2007),

van Lamsweerde, Axel *Requirements Engineering: From System Goals to UML Models to Software Specifications*, Wiley & Sons, NY (2009)..

Weiss, Joseph .W. and Don Anderson, Jr. "CIOs and IT Professionals as Change Agents, Risk and Stakeholder Managers: A Field Study," *Engineering Management Journal*, 16:2 (2004) pp. 13-18.

Wilhite, Allan. and Robert Lord, "Estimating the Risk of Technology Development," *Engineering Management Journal* 18:3 (2006) pp. 3-10.

SRA, Society for Risk Analysis website, <www.sra.org>, cited April 6 (2010).

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