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## **Prospective Safety Analysis and the Complex Aviation System**

Brian E. Smith  
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May 2013

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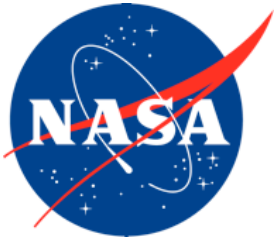
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## Acronyms and Definitions

AIRs .....	Aerospace Information Reports (published by the SAE S-18 Committee)
ALARP .....	as low as reasonably practical
ASAP .....	Aviation Safety Action Program
ASIAS .....	Aviation Safety Information Sharing and Analysis System
CAST .....	Commercial Aviation Safety Team
CNS.....	communications, navigations, and Surveillance
CPDLC .....	controller pilot data link communication
ECAST.....	European Aviation Safety Team
EGPWS .....	enhanced ground proximity warning system
EMF .....	electromagnetic field
FAA .....	Federal Aviation Administration
FAA AC.....	Federal Aviation Administration Advisory Circular
FAST.....	Future Aviation Safety Team
JIMDAT.....	Joint Implement Measurement Data Analysis Team
MIDAS .....	Man-machine Integrated Design and Analysis System
MSAW .....	minimum safe altitude warning
NASA .....	National Aeronautics and Space Administration
SAE.....	Society of Automobile Engineers
SMS .....	Safety Management System
SRM.....	Safety Risk Management
TLS .....	Target Level of Safety
TRIAD .....	Tool for Risk Identification and Display
UAS .....	unmanned aircraft system

# Prospective Safety Analysis and the Complex Aviation System

Brian E. Smith

*“If there is one attitude more dangerous than to assume that a future war will be just like the last one, it is to imagine that it will be so utterly different we can afford to ignore all the lessons of the last one.”*

John C. Slessor (1897–1979) from *Air Power and Armies*© 1936.

## ABSTRACT

Fatal accident rates in commercial passenger aviation are at historic lows yet have plateaued and are not showing evidence of further safety advances. Modern aircraft accidents reflect both historic causal factors and new unexpected “Black Swan” events. The ever-increasing complexity of the aviation system, along with its associated technology and organizational relationships, provides fertile ground for fresh problems. It is important to take a proactive approach to aviation safety by working to identify novel causation mechanisms for future aviation accidents before they happen. Progress has been made in using of historic data to identify the telltale signals preceding aviation accidents and incidents, using the large repositories of discrete and continuous data on aircraft and air traffic control performance and information reported by front-line personnel. Nevertheless, the aviation community is increasingly embracing predictive approaches to aviation safety. The “prospective workshop” early assessment tool described in this paper represents an approach toward this prospective mindset—one that attempts to identify the future vectors of aviation and asks the question: “What haven’t we considered in our current safety assessments?” New causation mechanisms threatening aviation safety will arise in the future because new (or revised) systems and procedures will have to be used under future contextual conditions that have not been properly anticipated. Many simulation models exist for demonstrating the safety cases of new operational concepts and technologies. However the results from such models can only be as valid as the accuracy and completeness of assumptions made about the future context in which the new operational concepts and/or technologies will be immersed. Of course that future has not happened yet. What is needed is a reasonably high-confidence description of the future operational context, capturing critical contextual characteristics that modulate both the likelihood of occurrence of hazards, and the likelihood that those hazards will lead to negative safety events. Heuristics extracted from scenarios, questionnaires, and observed trends from scanning the aviation horizon may be helpful in capturing those future changes in a way conducive to safety assessment. What is also needed is a checklist of potential sources of emerging risk that arise from organizational features that are frequently overlooked. The ultimate goal is to develop a pragmatic, workable method for using descriptions of the future aviation context, to generate valid predictions of safety risks.

# 1. Introduction

## 1.1 System Complexity

Commercial aviation at the beginning of the 21<sup>st</sup> century is a highly complex system of systems. It features airborne, ground, and space-based technology elements, complex supply chains, a comprehensive certification and operations regulatory environment, a diverse multitude of operators at many levels, and a complex web of operational procedures and training systems for those operators. Commercial aviation possesses the fundamental characteristics of diversity, connectedness, interdependence, adaptation, non-linearity, and emergent behavior that are found in complex systems (Page, 2007). Owing to its distributed architectures and redundancies, this complex system of systems can be extraordinarily resilient. Conversely, the interdependent relationships and characteristics of emergent behavior can result in the rapid propagation of undesired states through the system, with a risk of evolving into singular, spectacular, tragic events. Although the behavior of the commercial aviation system can be extremely sensitive to subtle and rare events, broadly speaking it demonstrates characteristic repeatable generic safety-risk behaviors (International Risk Governance Council, 2011). Predicting these characteristic system behaviors is a key goal for aviation safety, and underlies research based on both retrospective data analysis as well as formal modeling techniques.

## 1.2 Aviation “Diagnostics”

A great deal of work is currently taking place to improve our ability to sense and recognize signals of change that are weak (or buried in noise) but operationally significant. Much of this activity is centered on extraction of useful insights from repositories such as the Aviation Safety Information Sharing and Analysis System (ASIAS). The “Big Data” that is part of this collection has four important characteristics<sup>1</sup>: 1) It comes in at high velocity; 2) It is generated in high volumes; 3) It contains a wide variability of heterogeneous types (continuous and discrete signals, textual information often with non-standardized taxonomies and data descriptions); and 4) It has a wide variation in quality. Sensors generating the raw signals often fail at higher rates than the systems they monitor. Although the analysis of such large, heterogeneous repositories of operational data can find unknown statistical correlations in massive datasets, the “haystacks” are growing exponentially yet the “needles” found by the analyses may not all have the same value. Big Data by itself cannot differentiate between spurious and operationally significant correlations to fully assess social factors for accidents, and the context of human decisions in moments of crisis. For this reason, the human analyst will always be required. In addition, the results of analysis of huge datasets are subject to the vagaries of how the data is structured and analyzed (Brooks, 2013). Big Data is historical and is, necessarily, looking in the rear-view mirror. Other than the limited period of time for which extrapolations and seasonal trends from those data are valid, Big Data cannot, without assistance from human analysts, generate reliable looks into the future (although some historical conclusions can be extended to short-term future time horizons over which seasonal trends can be extrapolated). Future safety risk in aviation will derive from familiar causal and contributing factors that generate the same bad outcomes, but in new ways, operating in future contexts that haven’t happened yet, and will diverge from past trends.

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<sup>1</sup> Articulated by Dr. Ashok Srivastava, formerly of NASA Ames Research Center



From a predictive viewpoint, there are weaknesses in risk analysis based solely on event occurrences (Fletcher, 2012):

- Unless information across and within each level is effectively integrated, the analysis may not encourage “systems thinking.”
- It is reactive to existing threats buried in mounds of data and may not be predictive beyond a near-term timescale.
- It does not have the ability to identify deep systemic problems such as organizational or external factors in the surrounding environment *that are not part of any of the datasets used for the safety analysis.*
- It captures only unsatisfactory workplace conditions and events not systemic functional problems.
- It may not fully identify mitigations for emergent hazards arising within complex systems. The demonstrated precursors of unacceptable risks today could very well be among the precursors whose confluence will influence the safety risks of the future.
- Often, event occurrence data do not record what happened “when things went well” — what enabled the involved parties to avoid the accident or incident.

Stakeholder groups frequently predict changes affecting aviation as part of normal due diligence. These predicted changes could be contrasted with actual changes detected using monitoring methods. The quadrants in Figure 1 illustrate the notional categories of the resulting comparisons (Thiel, 1961).

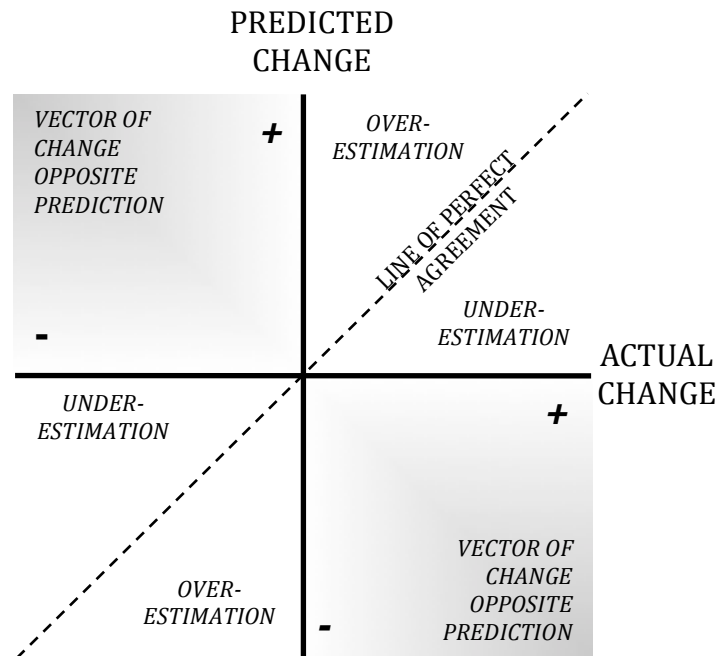


Figure 1. Notional categories of the resulting comparisons.

In some cases, predictions will be accurate (along the 45-degree line). Various sectors of those quadrants include over-estimation, under-estimation, and the shaded quadrants in which the vector of actual change is actually *opposite* the prediction, so-called “turning points.” These conditions can

often lead to ruptures—sudden discontinuities in a stream of events that are continuous under normal circumstances—and Black Swan<sup>2</sup> events (Taleb, 2010). The “rupture” problem is a characteristic of Catastrophe Theory, where tiny differences can result in large downstream changes due to non-linear system dynamics.

Looking at only the population of observed past events, probability is defined as the number of successful trials divided by the total number of (successful and unsuccessful) trials. For some classes of problems, it may be possible to estimate from observed distribution the probability of events more extreme than any yet observed. But probability in the future sense of risk is a “degree of belief” about the likelihood of future events. Risk estimation for the future chance of loss might come from highly sophisticated modeling and simulation derived from statistical analyses of past experiments or operational data. Various modeling approaches seek to reduce or at least bound the uncertainty.

### 1.3 The Uncertain Future

Unpredictable, disruptive changes will alter the nature and estimates of the magnitudes of residual risk. These unforeseen phenomena can and will happen.

In other words, the ultimate goal is to make decisions today to avoid unacceptable risks likely to emerge tomorrow—to manage both existing risks that could evolve and become unacceptable as well as entirely new risks. The prospection workshop technique described in Section 3 of this memorandum may be very helpful in this regard. The International Risk Governance Council<sup>3</sup> has identified three categories of technology-related emerging risk (International Risk Governance Council, 2011) as shown in Table 1.

There is an implicit assumption that in order to make decisions today to control the three categories of risks described above that are likely to emerge tomorrow, there is a need to identify these risks, analyze them, and assess their potential impact...as we do to make decisions today to control today’s risks. Although intuitively sound, this assumption relies on another assumption that is: *It is possible to fully identify, characterize, analyze, and assess tomorrow’s risks.*

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<sup>2</sup> Taleb defines a Black Swan as a random event satisfying the following three properties (Taleb, *The Black Swan: Why Don’t We Learn that We Don’t Learn?*, 2004): large impact, incomputable probabilities, and surprise. First, its occurrence has a disproportionately large impact -the impact being extremely large, no matter how low the associated probability. The expected impact times its probability, if quantified, would be significant. Second, the events have a small but incomputable probability based on prior information. Third, a vicious property is its surprise effect: at a given time of observation there is no convincing set of precursors pointing to an increased likelihood of the event.

<sup>3</sup> <http://irgc.org/>

Table 1. Technology-Related Emerging Risk

<i>Category</i>	<i>Dominant Feature</i>	<i>Governance Issue</i>	<i>Examples</i>
Uncertain impacts: Uncertainty resulting from advancing science and technological innovation.	Lack of knowledge and experience about consequences that could result from deploying new technology.	Given the uncertainties about potential consequences, what risk management measures are adequate and needed for technologies, processes or products with significant benefits but unknown risks?	<ul style="list-style-type: none"> <li>• Products and processes in nanotechnology or synthetic biology.</li> <li>• Health impacts of EMF.</li> <li>• Carbon capture and storage technologies.</li> </ul>
Systemic impacts: Technological systems with multiple interactions and systemic dependencies.	System complexity and interconnectedness: Loss of safety margins within evolving and interacting (complex) systems.	On-going examination of the state of the system and planning for its future (Are safety margins adequate? Are the right choices being made for system components as the system evolves in time?).	<ul style="list-style-type: none"> <li>• Utility networks (gas and electricity).</li> <li>• Ecosystems.</li> <li>• Climate change.</li> </ul>
Unexpected impacts: Established technologies in evolving environments or contexts.	Surprises from knowable risk factors: Unforeseen or changed circumstances.	Governance may seem to be well established but may in fact be inadequate for a variety of reasons. (Is there complacency, resulting in failure to observe and adapt to changing, potentially dangerous, conditions?)	<ul style="list-style-type: none"> <li>• Commercial aviation safety.</li> <li>• Nuclear power.</li> <li>• Ageing of infrastructures.</li> </ul>

## 1.4 Challenges of Rare (Accident) Events

The common features of major aviation accidents fitting into the rare event category are all too familiar (Duffey, 2011). These characteristics are sometimes called the Seven Themes, covering the aspects of causation, rationalization, retribution, and prevention. A poignant example is the Air France 447 accident.

The Seven Themes are described in the following paragraphs.

**First:** Major losses, failures, and outcomes all share the very same and very human four phases or warning signs:

- Unfolding of the precursors and initiating circumstances
- Confluence of events and circumstances in unexpected ways
- Escalation where the unrecognized unknowingly happens
- Denial and blame shift before final acceptance

**Second:** As always, these incidents all involving humans, were not expected but clearly understandable sometimes due to management emphasis on production and profit rather than safety and risk, from gaps in the operating and management requirements, and from lax inspection and inadequate regulations.

**Third:** These events have all caused a spate of media coverage, retroactive soul-searching, “culture” studies and surveys, regulation review, revisions to laws, guidelines and procedures, new limits and reporting legislation, which all echo perfectly the present emphasis on limits to the “bonus culture” and “risk taking” that are or were endemic in certain financial circles.

**Fourth:** The failures were so-called “rare events” and involved obvious dynamic human lapses and errors, and as such do not follow the usual statistical rules and laws that govern large quasi-static samples. Static samples, or the multitudinous outcome distributions (like normal, lognormal and Weibull) that dominate conventional statistical thinking, but clearly require analysis and understanding of the role of human learning, experience and skill in making mistakes and taking decisions.

**Fifth:** These events all involve humans operating inside and/or with a system, and contain real information about what we know about what we do not know, being the unexpected, the unknown, the rare and low occurrence rate events, with large consequences and highlighting our own inadequate predictive capability, so that to predict we must use Bayesian-type likelihood estimation.

**Sixth:** There is the learning paradox, that *if we do not learn we have more risk, but to learn we must perversely have the very events we seek to avoid*, which also have a large and finite risk of re-occurrence; and we ultimately have more risk from events we have not had the chance to learn about, being the unknown, rare or unexpected.

**Seventh:** These events were all preventable but only afterwards. 20/20 hindsight, soul-searching, and sometimes massive inquiries reveal what was so obvious time after time: the same human fallibilities, performance lapses, supervisory and inspections gaps, bad habits, inadequate rules and

legislation, management failures, and risk taking behaviors all should have been—and were—self-evident and yet were left uncorrected. People learn and retain lessons; organizations much less so.

We claim to learn from these themes each time, perhaps introducing corrective actions and lessons learned, thus hopefully reducing the outcome rate or the chance of re-occurrence.

In aviation, there is currently broad consensus on a set of undesirable events and conditions that are on the minds of the aviation safety community—the things that keep safety experts up at night.

Exemplar issues include:

- Aircraft controllability in adverse situations
- Deviations from air traffic control clearances
- In-flight fire, smoke, and fume events leading to ATB/diversions, customer evacuations
- Loss of separation
- Safety Net Penetration (terrain awareness warning systems/traffic collision avoidance systems/minimum safe altitude warning systems)
- Loss of navigation capability
- Passenger injury
- High-speed rejected take-offs
- Runway excursions
- Runway incursions
- Fuel starvation, leakage
- Stall warnings
- Unusual attitudes
- Aircraft mis-configured for take-off
- Abnormal runway contact
- Loss of or unreliable air data
- Unstabilized approach
- Cabin/in-flight safety/turbulence
- Landing safety
- Lithium batteries/HazMat/DG
- Automation dependence/integration of modern cockpit and effect on piloting skills
- Stall/upset recovery
- Maintenance safety (safety programs: Aviation Safety Action Program reporting; ‘just culture;’ significant maintenance program cost overruns)
- Weight and balance; cargo handling
- Bird strikes
- Loss of control
- Experience level of pilots and mechanics
- Timely weather intelligence
- Procedural compliance for key operational items such as flap extension, weight and balance determination, and deicing
- Safety support and integration with Fatigue Risk Management Program (Part 117)
- Training: programs—content, duration, pace
- Rapid expansion/consolidation; effect on operations across the board
- Fatigue and duty time (to include all employee groups)
- Contaminated runway operations

Prediction of the precursors of these events and conditions from prospective analysis is the goal of any team looking ahead at safety. Such teams desire to identify novel future ways to generate the same set of historic bad outcomes: collision with ground or another object and in-flight breakup (deaths due to in-flight turbulence and terrorism not included).

## **1.5 Black (and White) Swans**

The reader is reminded that risks, manifesting themselves as accidents in the future, will almost certainly include “Black Swan” events—those that have a surprisingly major impact (to the observer) yet after the fact are rationalized by hindsight, as if they should have been expected. That is, relevant data were available but unaccounted for in Safety Risk Management (SRM) programs. But not all future aviation accidents will be Black Swans. Some of the most recent accidents are well known White Swans (e.g. runway excursions) and significant efforts are underway to implement the known and available solutions for these historic accident types.

The Black Swan theory explains:

- the disproportionate role of high-impact, hard-to-predict, and rare events that are beyond the realm of normal expectations in history, science, finance, and technology.
- the difficulty of predicting the probability of consequential rare events using scientific methods (owing to the very nature of and non-Gaussian, log distribution of small probabilities and the variability of human performance in novel situations).
- the psychological biases that make people individually and collectively blind to uncertainty and unaware of the massive role of rare events in historical affairs.

A challenge for proactive safety assessment of future systems is overcoming the shortcomings of approaches based solely on retrospective analysis of the accident, incident, and operational data within the well-known Heinrich pyramid (SKYbrary, 2011). This pyramid theory postulates that the number of events and their characteristics that occur in a lower level of the pyramid are precursors for the events occurring in the level above. As both the reliability of components/systems and the complexity of those systems increases especially in newer fleets, the dynamic interactions and interdependencies among the technical, human, and organizational factors will become the dominant sources of risk in the future aviation system.

## **1.6 Challenges of Modeling**

There are at least three challenges faced by current safety models:

- First, some traditional models do not capture the complexity of the commercial aviation system in sufficient detail to provide emergent predictions. Linear models, such as event sequence diagrams and fault/event trees, fit into this category. Those that do generate emergent behaviors require significant effort to fully model the path-dependent, behavioral transitions in multi-agent cooperative control systems (Valiusaityte, 2010). Models that can capture emergent behavior such as Air Man-machine Integrated Design and Analysis System (Air MIDAS) require modeling of the underlying structures such as memory and cognition that interact within a human operator during execution of a sequence of tasks and produce possible branch points (Gore, 2002).
- Second, some models are unable to detect and simulate “cascading failures,” where a failure of one component in a system can cause failures of other components. The more tightly the

components are coupled, the faster and further a shock or failure can propagate throughout the system. It is usually not a single predictable failure that turns incidents into accidents; it is the second or third one that comes out of the blue at the same time one—as illustrated in the well-known reason “Swiss-cheese” model (Reason, 1997).

- Third, it is extremely difficult to appropriately characterize the world of tomorrow. No model can provide useful predictions with an inaccurate picture of the environment being modeled<sup>4</sup>. This future world is a critical “boundary condition” or set of assumptions. When model results are presented there is a requirement to articulate the simplifying assumptions describing the complex systems that is the focus of the safety analysis. Even the prospection-based approach proposed in this paper may not be any less subject to this problem.

## 1.7 Contributing Factors to Emerging Risk

Commercial aviation contains an extraordinarily large number of hazards and safety nets. It is therefore critical to focus scarce resources on critical hazard generation mechanisms that affect key safety nets in order to produce high-value solutions. Unforeseen hazards can emerge from indirect factors that have been articulated by the International Risk Governance Council (see Table 2 on the next page).

If robust and repeatable means to detect early signals of risk leveraging these factors are not systematically employed, there is a large chance that the emerging risks will materialize with maximum impact, given that no one saw them coming in time to undertake prevention or mitigation efforts.

It is particularly important to systematically address reasons for not detecting future risk, how to know what to look for, and then what to do with the resulting information. The following is a list of these phenomena (emerging risks: sources, drivers, and governance issues, 2010):

- Detecting “hidden” concentrations or accumulations of hazard and risk exposures whose size, scale and impact could have a material adverse effect.
- Complex and “opaque” products or services which are understood by only a few experts.
- Looking for discontinuities or tipping points which indicate either unclear “rules of the game” or a likely change.
- Lengthy dependent “chains” of any type since they are only as strong as the “weakest link.”
- More scenario analysis and “stress testing” outside the range of “business as usual.”
- Imagining unintended consequences of public policy and regulation, and looking for connections which could arise between “seemingly unrelated” trends.
- Measuring trends in diverging views between groups on critical issues such as automation implementation, flight crew training and demographics, and the changing regulatory landscape, since such diverging views can be precursors to emerging risks or can complicate efforts at taking precautionary or mitigation measures. The FAA Safety Risk Management Policy Directive 8040.4 Rev A describes how various lines of business in that agency are to handle hazards once identified. If various FAA lines of business disagree on identified hazards, that itself is a signal that those specific hazards must get escalated within the 8040.4A management framework.

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<sup>4</sup> Communication from Dr. Alfred Roelen, Dutch Aerospace Laboratory, NLR, November 2011.

Table 2. Indirect Sources of Hazards

<i>Indirect Source</i>	<i>Description of the Factor</i>
Scientific unknowns	Whether tractable or intractable, these unknowns may or may not contribute to risks being unanticipated, unnoticed, and over- or under-estimated.
Loss of safety margins	The subtle loss of the slack or buffering capacity in tightly coupled systems operating at higher levels of stress.
Positive feedback	Amplification of a change or a perturbation that can be destabilizing and amplify consequences of emerging risk.
Varying susceptibilities	Risk susceptibilities differing from one population to another. E.g., risk to airlines operating in mountainous regions versus oceanic.
Conflicting interests	Occur when risk management efforts encounter opposition on the basis of contested science or interpretations of data/values.
Social dynamics	The broader context of group perception that can lead to narrow attribution of risks to solely technology or human performance failures.
Technological advances	Technology change not accompanied by adequate scientific investigations of system-wide consequences and adequacy of regulatory frameworks.
Temporal asynchronicity	Risk may be amplified if it fails to emerge within a period permitting early detection or beyond near-term time horizons of concern to economists and politicians.
Communication	Risks complicated or amplified by untimely, incomplete, misleading or absent communication.
Information asymmetry	Needed risk information held by some stakeholders and not available to others either intentionally or inadvertently creating mistrust and non-cooperation.
Perverse incentives	Risks appearing when a “checklist mentality” pervades an organization with people trying to meet pre-set indicators rather than embracing a safety culture. Examples in aviation domain:
Malicious acts	Human threats are not new but in a global system with more interconnected infrastructure consequences may be more far-reaching than in the past.

At least four information-processing operations typically take place in real world settings when unexpected, emergent events occur: 1) Awareness; 2) Diagnosing; 3) Choosing a course of action; and 4) Responding. People and organizations often do not notice unexpected events, even if these events are relatively salient. This phenomenon is known as *change blindness* (McConkie, 1996).



Many tragedies in aviation can be associated with failures to detect and respond to off-nominal events—both those occurring in operational flight setting and those having organizational roots. Jones argues that the majority of safety breakdowns have their origin in the first phase (awareness or noticing) rather than at later stages of information processing (Jones, 1996).

Conceptual roadblocks at the organizational level can also result in failure to detect an evolving crisis or emerging risk (from Robert Bea, U.C. Berkeley Center for Catastrophic Risk Management). Slow phase transitions are often difficult to detect, as are the events and conditions that trigger sudden ruptures. Safety risk analysts can benefit from concept of the “Dancing Landscape<sup>5</sup>.” The closer a person is to the action such as a pilot, air traffic controller, or mechanic, the more aware they are that the safety landscape is not static. Because of the dynamic character of “dancing landscapes,” what to monitor among all available aviation data for weak signals of impending events also becomes critical. As stated by Sidney Dekker:

*“All open systems [such as commercial aviation] are continually adrift inside their safety envelopes. Pressures of scarcity and competition, the intransparency and size of complex systems, the patterns of information that surround decision makers, and the incrementalist nature of their decisions over time, can make...systems drift into failure. Drift is generated by normal processes of reconciling differential pressures [and future changes] on an organization (efficiency, capacity utilization, safety) against a background of uncertain technology and imperfect knowledge. Drift is about incrementalism contributing to extraordinary events, about the transformation of pressures of scarcity and competition into organizational mandates, and about the normalization of signals of danger so that organizational goals and “normal” assessments and decisions become aligned. In safe systems, the very processes that normally guarantee safety and generate organizational success can also be responsible for organizational demise. The same complex, intertwined socio-technical life that surrounds the operation of successful technology is to a large extent responsible for its potential [future] failure.*

*Drift into failure is hard to recognize because it is about normal people doing normal work in (seemingly) normal organizations, not about obvious breakdowns or failures or errors.” (Dekker, 2005)*

## 2. The Prospective Approach

Prospective safety methodologies offer a fresh approach to risk management. The prospective approach looks beyond past observations for insight to the future; it actively seeks out and explores multiple, believable future paths (as opposed to singular “predictions”) that may be relevant to a target safety issue. Prospective approaches can have great value as early assessment tools that don’t require elaborate modeling structures. Merriam Webster lists the principle meaning of ‘prospection’ as “the act of anticipating (foresight);” one subsidiary meaning is “the act of exploring (as for gold),

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<sup>5</sup> In the “dancing landscape” concept, Dr. Scott Page of the University of Michigan postulates that safety landscapes have local peaks and valleys corresponding to specific parameters of interest. These landscapes are relatively easy to navigate if they are fixed and don’t move with time. “Dancing landscapes” in the complex aviation system cause shifts of the peaks and valleys over time due to the novel structures and patterns arising from the complex set of interdependent, diverse, interacting, and interdependent agents and organizations present in aviation. It’s easy to lose one’s safety footing on a dancing landscape.

and we do indeed hope to create high value. The greatest challenge for the assessment of emerging risks is to identify credible failure scenarios that have a relatively high likelihood. Some uncertainty about the future cannot be eliminated, because multiple future paths have non-zero likelihood.

## **2.1 Conceptual Framework**

Up to this point, it has been assumed that the reader is aware of the definitions of common safety terms. In some cases there are nuances to these definitions that are commonly used but not fully understood. In the following section two similar-sounding but slightly different concepts are defined and discussed: *prediction* and *prospection*. An understanding and appreciation for the key differences between these two concepts will be critical for development of an effective methodology for assessing future risks. Such a method or methods may have fundamentally different characters depending on whether they approach future risk from a predictive or prospective viewpoint.

## **2.2 Definition of Prediction**

- Estimates of the nature of the future environment informed by expert subject-matter opinion
- Results from simulation models based on known, deterministic relationships
- Quantitative trend extrapolations

## **2.3 Definition of Prospection**

Prospection is “the act of looking forward in time or considering the future” (Gilbert, 2006). It has also been used for several years in the field of Future Studies (Future Studies, 2013), and is defined to be “the activity of purposefully looking forward [i.e. into the future] in order to create forward views and/or images of the future” (Voros, 2009). Prospection identifies disruptive technologies, events, and conditions within aviation, some being impossible to predict, surprise influences from external domains not intuitively expected to be the sources of hazards and risks, and suggests unexpected uses of technology not anticipated by the original designers, etc. Unexpected uses of technology or disruptive events can be revealed by the construction of scenarios. Extrapolative prediction and prospective prediction are the two fundamental approaches to identifying hazards and risks in the future.

In contrast to extrapolative prediction, prospective prediction assumes that the future cannot be derived solely through extrapolation but that sudden and unanticipated discontinuities in a stream of events may occur. Table 3 illustrates the fundamental conceptual differences between these two concepts.

Table 3. Extrapolative Prediction and Prospective Prediction Differences

<i>Extrapolative Prediction</i>	<i>Prospective Prediction</i>
<ul style="list-style-type: none"> <li>• Aims at predicting the future.</li> </ul>	<ul style="list-style-type: none"> <li>• Aims at helping “build” the future.</li> </ul>
<ul style="list-style-type: none"> <li>• Frequently focuses on an individual variable.</li> </ul>	<ul style="list-style-type: none"> <li>• Global/systemic approach (considering all perspectives via multidisciplinary teams).</li> </ul>
<ul style="list-style-type: none"> <li>• Essential to quantification.</li> </ul>	<ul style="list-style-type: none"> <li>• Combines qualitative and quantitative dimensions.</li> </ul>
<ul style="list-style-type: none"> <li>• Utilizes the continuity principle: that future evolutions are incremental extensions of past developments.</li> </ul>	<ul style="list-style-type: none"> <li>• Takes into account ruptures, acknowledging the acceleration of social, technological, and economic changes.</li> </ul>

To be effective a prospective prediction approach must (Cagnin, 2007):

- *Look forward* (e.g. through forecasting, trend analysis, gaming and scenarios, futurist writing, etc.)
- *Look across* (e.g. through systemic thinking)
- *Look backwards* (through historical analogy<sup>6</sup>, previous future-oriented studies, trend analysis, etc.). *History is important.*

For any predictive safety process, it is important to understand the implications of the underlying conceptual framework on the process itself and on the expected outcomes.

Conceptual Framework 1. The simplest conceptual framework would consider a *single* predicted (most likely) future scenario as input.

Conceptual Framework 2. A refinement of this conceptual framework would consider a set of *possible scenarios* (the most likely ones), each of them being studied and considered as certain when studied, the final result being a combination of the various independent analyses of the various scenarios.

Conceptual Framework 3. A more sophisticated conceptual framework would consider that *there is no way to define a scenario or a set of scenarios* (fixed or considered certain when studied), but that uncertainty is part of the very nature of the input.

Whether an anticipatory method is developed using conceptual frameworks 1 and 2 or 3 has an impact on the methodology itself, hence on the results. The difference between conceptual framework 1 and conceptual framework 2 lies more in the implementation of the method and on the results than on the nature of the method (Smith, 2012).

The concepts of *prospection* and *proactive strategy* are intimately related, yet they remain distinct entities. Therefore it is necessary to distinguish between: 1) the anticipatory *prospective* phase: in other words, the study of possible and desirable changes, and 2) the *proactive* phase. In other words, the working out and assessing of possible strategic choices so as to be prepared for expected changes (pre-activity) and provoke desirable changes (pro-activity) (Godet M. w., 2010).

<sup>6</sup> Henry Kissinger once remarked, “History is not, of course, a cookbook... It teaches by analogy, not by maxims.”

## 2.4 Scenarios as Aids to Prospecction

When the world is highly unpredictable and we are working from a limited range of expectations, belief constructs involving safety will frequently be proved wrong. Scenario planning offers a framework for developing more resilient policies and practices when faced with uncontrollable, irreducible uncertainty. A scenario in this context is an account of a plausible future. Scenario planning consists of using a few contrasting scenarios to explore the uncertainty surrounding the future consequences of a specific technology decision or safety issue. Ideally, scenarios should be constructed by a diverse group of people for a single, stated purpose. Scenario planning can incorporate a variety of quantitative and qualitative information in the decision-making process. Often, consideration of this diverse information in a systemic way leads to better decisions. Furthermore, the participation of a diverse group of people in a systemic process of collecting, discussing, and analyzing scenarios builds shared understanding (Peterson, 2003).

Hidden risks that we can't name a priori maybe revealed by construction of scenarios. A scenario may be an especially important ingredient for the prospecction process:

- Postulating the intersection of unpredictable disruptive technologies, events, and conditions within aviation and the surprise influences from external domains.
- Suggesting unexpected uses of technology—plus attendant novel hazards and risks—not anticipated by the original designers.

Often the telltale signs of risk do not manifest themselves in actual exposure to, say high-visibility fatal accident types—such as controlled flight into terrain, loss of control, and system component failures—but may be found in threats observed in high-risk incidents that didn't result in fatalities. Decisions and actions by maintenance personnel, accuracy of weather predictions and how they get communicated, personnel training/demographics, and a host of other phenomena can trigger or amplify the threats that are present in the system.

As the aviation community looks into the future, key questions must be addressed within the risk control process:

- Does the risk exceed an acceptable level (e.g., regulatory standards, action levels)—the “As Low As Reasonably Practical” (ALARP) test?
- What steps might be taken to reduce or eliminate the remaining risks?
- What is the effectiveness of those risk countermeasures against the threats?
- What is an appropriate balance among risks, benefits, and resources to manage risks?
- Will new, unknown risks appear in the future as a result of present or planned management steps to control the known risks?
- What is the net effect of risks, mitigations, and new hazards introduced by the mitigations: the so-called “residual risks?”

Regardless of the method or technique used to manage future risk, two essential ingredients are necessary for prospective insight and practicality:

- A sufficiently broad picture of the future (from plausible scenarios) including contributing factors to hazard and risk generation that users of the method might not naturally consider.

- Guarantees that key front-line personnel such as pilots and air traffic controllers with knowledge of the dynamic hazard environment participate in the application of the risk assessment method. Safety analysis must not occur in a vacuum that excludes this operational expertise.

Without both ingredients, no method used by an analysis team regardless of how theoretically robust it may be will yield practical results.

As the prospective approach will reveal, *risk events are about the uncertain, complex futures, which cannot be predicted precisely*. If an event does occur, then maybe it is a problem to be solved and avoided in the future but it is no longer a potential risk event. So, prospective risk assessment is about being ready—about “future-proofing” aviation—not trying to precisely predict it. This is where the range of possible futures offered by the prospection process and scenario development comes in.

Several major factors and useful measures that influence the prediction of risk and stability in financial systems, based on what we observe for all other systems with human involvement. These factors must be considered in any predictive methodology.

1. Duffey’s Universal Learning Curve (Duffey, 2011) provides a comparative indication of learning due to observed trends.
2. The probability of failure/loss is a function of experience or risk exposure.
3. One relevant measure of failure is the rate of fatal aircraft accidents; there may be others.
4. A relevant measure of experience and risk exposure could be the accumulated flight hours for a crewmember or the number of flight operations.
5. Stable systems are learning systems that reduce complexity.
6. An absolute measure of risk and uncertainty is the Information Entropy<sup>7</sup>, which reflects *what we know about what we do not know*.
7. Unique conditions exist for systemic stability.
8. Repeat events are likely—the so-called “cosmic cycles of accidents” in which the people who remember the lessons learned from major accidents move on and the organizations do not consciously retain those lesson learned. *Re-awareness maybe one of the biggest issue facing safety*. Monitoring the trends in “hits” on “lessons learned” organizational websites may provide indicators of the efficacy of transmission of wisdom and insight to newer personnel.
9. *Existing systems are unstable unless learning is continually occurring*. This has great significance for the western aviation system in which fatal accidents are in that category of statistically extremely rare events.
10. *New systems are unstable during initial periods when experience is negligible*.

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<sup>7</sup> Information Entropy is a concept from information theory. It tells how much information there is in an event. In general, *the more uncertain or random the event is, the more information it will contain*. Random, “Black Swan” events therefore can contain a great deal of insightful information about connections and failure mechanisms we didn’t know about. Mathematician, Claude Elwood Shannon, created the concept of information entropy.

Within the possible futures are:

- major trends for which indicators can be found in today's information
- major uncertainties for which there is consensus among safety experts
- possible changing conditions and ruptures affecting aviation that no one can predict

Heuristics can be a significant aid to prospection and future system characterizations. People rely on a limited number of heuristic principles that reduce the complex task of assessing probabilities. In general, these heuristics are quite useful, but sometimes they can lead to severe and systematic errors. The subjective assessment of probability resembles the subjective assessment of physical quantities such as distance or size. These judgments are all based on heuristic rules.

For example, the apparent distance of an object is determined in part by its clarity. The more sharply an object is seen [as a result of, say a lack of atmospheric haze], the closer it appears to be. However, reliance on this rule can lead to systematic errors in the estimation of distances (Kahneman, 1982). This was the experience of Apollo astronauts on the moon. The lack of an atmosphere made objects on the distant horizon appear much closer than they really were.

In addition, the elicitation of unbiased judgments and the reconciliation of incoherent assessment [from the personal heuristics employed by multiple human raters] pose serious problems [for Bayesian methods] that presently have no satisfactory solution (Lindley, 1979) (Shafer, 1983).

## **2.5 Heuristics as an Aid to Prospection**

Heuristics can be an important aid in a prospective approach to risk analysis of complex aviation futures because they offer ways to:

- find resolution or discover trends.
- deal with complexity without losing information.
- summarize and/or organize experience.
- achieve powerful insight—sometimes with dry humor!

Exemplar heuristics that can apply to aviation safety include, but are not limited to:

- “A single insight is worth a thousand analyses.”
- “Contain excess energy as close to the source as possible.”
- “The thought that disaster is impossible often leads to an unthinkable disaster” (Weinberg, 1985).
- “When big systems fail, the failure is often big” (Gall, 2002).
- “The better adapted you are, the less adaptable you tend to be” (Weinberg, 1985).
- “A temporary patch will very likely be permanent” (Gall, 2002).

The Areas of Change list (Future Aviation Safety Team, 2012) compiled by the ECAST Future Aviation Safety Team is an example of predictive heuristics useful for prospective safety assessment. Exemplar future-trend heuristics from this list include:

- Increasing use of Controller Pilot Data Link Communication (CPDLC) for weather information and advisories/clearances.

- Shift from clearance-based to trajectory-based air traffic control.
- Increasing reliance on satellite-based systems for Communications, Navigations, and Surveillance (CNS) Air Traffic Management functions.
- Increased traffic flows involving closely-spaced parallel, converging, and intersecting runway operations.
- Increasing operations of military and civilian Unmanned Aerial Systems (UAS) in shared military, civilian, and special use airspace.
- Increasingly integrated and interdependent aircraft systems.
- Emergence of high-energy propulsion, power, and control systems.
- Increasing functionality and use of personal electronic devices by passengers and flight crew.
- Entry into service of commercial, space-tourism passenger vehicles.
- Shortened and compressed type rating training for self-sponsored pilot candidates.

### 3. A Prospection Workshop Technique

The following practical approach enables teams to identify and form into a hierarchy the main prospective “stakes” of the future—the strategic visions and priorities for aerospace manufacturers, operators, and regulators in the evolving landscape of tactical safety. A typical “stake” may be a target level of safety (TLS; a given percentage reduction in fatal aviation accidents; a reduction in the frequency of close-calls; or a desired increase in system throughput or flight delay reduction.

Such an analysis can be achieved by employing the 12-step workshop approach described below (Godet M. , 2004) . This is a suggested starting point to activate a futures mind set—it does not replace the detailed risk and controls assessments that may need to be carried out by a user organization.

Step 1. The leader of the analysis team asks participants to identify: a) expected; b) desired; and c) feared changes based on a particular future aviation system or concept of operation as they understand it as well as their notions of the future environment in which that system will be immersed. The Future Aviation Safety Team (FAST) Areas of Change list described earlier and similar reference prospective documents may provide useful input information.

Step 2. Identify the inertias—those forces which will tend to keep the system moving its current direction whether safe or vulnerable. Examples of safety inertias include existing safety nets such as Enhanced Ground Proximity Warning System (EGPWS), and Minimum Safe Altitude Warning (MSAW). Other types of inertias include external forces such as pilot supply and the inevitable introduction of Unmanned Aerial Systems in the airspace system. A suggested method for collecting these changes and inertias from the workshop participants is the so-called “635” Method<sup>8</sup>:

The “635” Method for knowledge elicitation consists of breaking an analysis team into groups of 6 persons each. Within each group, each of the six individuals is then given a worksheet with 18 rows and 2 columns: One for the changes and one for the inertias. The moderator then gives each

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<sup>8</sup> 635 Method: <http://www.thinkthru.info/methods/635-method.aspx>

person five minutes to identify no more than three changes and three inertias. At the conclusion of the first five minutes, each person passes the worksheet to the person on his or her right, and the process of filling in the next three rows continues. This process is complete when all six participants have filled in all worksheets over the course of a 30-minute time period. The advantage of the 635 technique is that it provides a very structured process; each person has the same opportunity to generate ideas because their creativity takes place “in secret” without dominance from personalities; it generates many ideas (6 persons x 3 ideas each x 6 5-minute time periods = 108 potential ideas) in a short time span; it features spontaneity; and it is suitable for untrained participants. The potential disadvantage of each person seeing the previous person’s inputs on the worksheet, and hence adding bias, is probably more than offset by the themes and interactions the participants begin to see among theirs and previously generated ideas.

Step 3. Individual results are presented to the group in order to build a common list of changes and inertias through several rounds of open discussions. To be effective and to limit bias, the individual results should be written, compiled, and completed by each individual (devoid of interaction with others in the group) before beginning discussion as described in the 635 method described above.

Step 4. Aggregate the individual preferences among the group in order to identify the five to ten major changes and inertias that appear to be, according to blind voting consensus, the major issues for the future.

Step 5. Place the consensus changes and inertias within matrices of *importance* (weak or strong along the ordinate) versus *level of control* of those inertias (weak or strong along the abscissa). (See Figure 2.)

Step 6. For both *critical changes* and *critical inertias*—those that are of high-priority because they are both *important* and over which we have *weak control*, conduct a group brainstorming session asking two questions that will move *critical changes and inertias* to the *desired outcome* quadrant:

- How can we reduce the importance (safety significance)?
- How can we strengthen their control?

The four quadrants in the matrix (Figure 2) break down as follows:

- A. Critical changes and inertias affecting future stakes: the important changes that we have not yet mastered (strong control).
- B. Important changes or inertias already mastered by aviation.
- C. Unimportant changes or inertias that are not yet mastered. (so-called “Guiltless Weaknesses”).
- D. Unimportant changes or inertias that may have been mastered some time ago. These inertias often feature prominently in safety discussions because



the community believes it has mastered them. (known as “Useless Strengths”).

The pending FAA Advisory Circular, AC 120-92A, that provides guidance for effective operation of a Safety Management System (SMS), states that the performance objective of SRM is to “develop processes to understand the *critical characteristics* of its systems and operational environment and apply this knowledge to identify hazards, analyze and assess risk and design risk controls.” Thus it is highly important to identify the *critical inertias and changes* embodied in the *critical [safety] characteristics* of the postulated aviation future (Quadrant A, Figure 2).

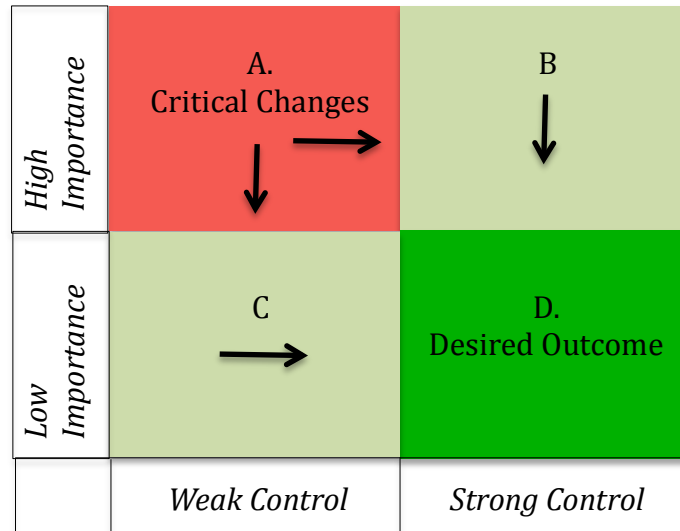


Figure 2. Diagram the changes and inertias within matrices of importance versus level of control.

Step 7. Identify the stakes and objectives for the future aviation system under study. A reminder: A typical “stake” may be a target level of safety (TLS) or a given percentage reduction in fatal aviation accidents or a desired increase in system throughput or flight delay reduction. The Tool for Risk Identification and Display (TRIAD) (Mauro, 2009) strongly suggests separate risk analysis for the major threat types or “stakes” of risk: fatal accident and injury, property damage, mission success (i.e., achieving desired fuel burn, delay reduction, reduced noise footprint, etc.), and the important—but often overlooked - factor known as social amplification<sup>9</sup>: the roles of the media and crisis management decisions in shaping the reactions of the public and thus determining indirect consequences that can be of crucial importance (BURNS, 1993).

Step 8. Identify the necessary actions (Objectives) in order to address the stakes and reach current system objectives and list them in Table 4.

<sup>9</sup> When a risk undergoes social amplification either within a technical domain or in media or legislative spheres of influence, the demand for action against the perceived risk may actually result in costs for new mitigations that are out of proportion to the actual risk across fleets and the aviation system. The requirement for costly new-airplane fuel tank inerting in response to the one-off TWA 800 accident may be an example of this phenomenon.





- Does this phenomenon render the projected safety systems more brittle to off-nominal conditions? If so, by what mechanism?
- Does this phenomenon decrease safety levels during non-normal or emergency operations within the projected future system of interest? If so, by what mechanism?
- What current and projected safety assurance measures within the future system of interest may be lost or rendered ineffective as a result of this phenomenon? If so, by what mechanism?
- Does this phenomenon require creation of new control measures for critical aspects of the future system? Definition: A control measure is an action or procedure that will reduce, prevent or eliminate a potential hazard. If so, by what mechanism?
- Does this phenomenon adversely affect critical control points or critical limits? Definitions: A critical control point is a step at which a control measure is applied. A control limit is a maximum and/or minimum value for controlling a physical parameter. If so, by what mechanism?
- Will this phenomenon create new conditions that are currently not part of the design assumptions for future systems and procedures? If so, by what mechanism?
- Will this phenomenon result in decreased skill levels and judgment among operators of future systems? If so, by what mechanism?

The following practical guidance will result in maximum success for such a workshop<sup>10</sup>:

- Permit adequate time for presentation, discussion, and understanding of the particular concept of operation or set of scenarios that will be the focus of the future safety risk assessment. Many safety and operational considerations will come up during the presentation of the concept under study if sufficient time is set aside. Operational experts that are not in the specific field of the concept under analysis come up with highly relevant insights as they get exposed to a more detailed briefing on the concept under study.
- Potential system-wide impacts that will emerge via consensus expert judgment should be recorded prior to beginning the change/hazard/risk assessment analysis exercise.
- An adequate level of specificity is needed when describing the estimated prevalence and other criteria characterizing a critical change. Avoid information that is too vague and therefore not actionable.
- Establish a hazard taxonomy and stick with it.
- Brainstorming discussions need to be conducted in a structured manner to prevent each person from being overly influenced by their own mental model<sup>11</sup>. Hazards and possible ruptures should be brainstormed in a group setting rather than individually. A richer set of material will emerge if the brainstorming is led by a trained facilitator.

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<sup>10</sup> From the lessons learned by the Future Aviation Safety Team in 2011 while developing a predictive safety methodology for the Joint Implement Measurement Data Analysis Team (JIMDAT) operating under the U.S. Commercial Aviation Safety Team (CAST).

<sup>11</sup> For guidance on effective structured brainstorming sessions see: H.H. De jong, *Guidelines for the identification of hazards: How to make unimaginable hazards imaginable*, Contract Report NLR-CR-2004-094, National Aerospace Laboratory NLR, 2004

- Unambiguous guidance must be given on how to approach the hazard and rupture identification process in order to yield consistent results.
- Broad themes will be relatively easy to identify. They will lend themselves to a systematic, matrix-based interaction analysis. These themes may be useful in conducting a Markov Network-style analysis of interaction paths leading from a fully-functioning systems to successively greater levels of:
  - Degraded system performance arising from the emergence of the identified hazards to a
  - Fully failed system state.
- What may be of most value to the aviation community is a list of *un-ranked* hazards (and potentially an organizational structure for them) that are generated and regularly updated by a dedicated, multi-disciplinary group of subject-matter experts. This list of possible future hazards may be a product that many organizations will incorporate into their existing, internal risk assessment process. Each stakeholder organization may have its own value system for prioritizing future hazards that are identified in the workshop process.
- Tangible products from any team looking ahead at safety will be most useful if they have the following features:
  - A continuously updated system-of-system definition the future so organizations can identify key phenomena that may impact the safety viability of the products they intend to market in the future. This future definition becomes the starting point for internal, anticipatory risk-reduction efforts.
  - A continuously updated set of future hazards and potential interaction paths leading to novel, potentially high-risk scenarios.

*These outputs may have great value for the research community because they will identify key future conditions and hazards for which research solutions should be developed.*

Furthermore, this set of outputs might be a natural fit within the set of Aerospace Information Reports (AIRs) published periodically by the SAE S-18 Aircraft and System Development and Safety Assessment Committee.

- The output of the workshop should include a means to identify and record the assumptions and risk factors in the future descriptions or scenarios. Risk factors may include an approach to identify and analyze non-related phenomena that may be important from a safety point of view.
- A final workshop product should be a list of specific phenomena to monitor for the emergence of system-wide and tactical vulnerabilities.

## 4. Conclusion

In order to form a reliable “prospective” picture of the future risk landscape in aviation, it is not enough to enquire about objectively measurable, rationally comprehensible hazards and risks (International Risk Governance Council, 2011). One must understand the factors driving the future risk landscape: changes in needs, interests, visions, hopes, and fears of the major players.

As with any safety assessment process, the users of prospective methods discussed herein must take into account how the results of the analyses and possible recommendations for corrective action will be used within the stakeholder organization. It may be necessary to pre-condition the recipients of the proposed prospective analysis approach to ensure that the results produce the needed response.

The prospection-based approach introduced in this paper is concerned with:

Question 1: What could happen?

Question 2: What can I do? The moment an organization begins to address this question the inquiry moves into the strategic realm. Once these first two strategic questions have been broached, the safety inquiry continues.

Question 3: What will I do?

Question 4: How will I do it?

The connection between *prospection* and *proactive* strategy occurs between (Question 2) and (Question 3) (Godet M. w., 2010).

For simple, linear systems, loss events can be precisely predicted if cause-and-effect relationships are known and all variables can be measured with sufficient accuracy. That is why fatigue life of certain aircraft components can be accurately predicted if sufficient testing and operational evidence is available.

For complex systems, however, accurate predictions are challenging. No one can predict where and in what context the next aviation accident will occur. Yet it is possible to estimate the risk, or average frequency and impacts of aviation accidents over, say the next year or two. Using the prospective approach outlined in this document, one may have increased confidence in looking down the road somewhat farther.

The real difficulty of future risk assessment is not complexity per se, but in the accelerated rate of change of complex systems. The faster the risk landscape changes or shifts under our feet, the more risks can remain largely unidentified by current methods or become incalculable. It is no longer just individual parameters but entire systems that are changing with increasing speed. For this reason, the potential for unpleasant surprises become greater (International Risk Governance Council, 2011). A prospective approach—utilizing the simple workshop technique described herein—offers the “prospect” for minimizing surprises in futures that may evolve along different, plausible paths.

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