Total aviation system safety assessment methodology

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This study initiates the development of a total aviation system safety assessment methodology that can be used across different aviation domains, during the different life-cycle phases of a newly proposed operation or system. It is concluded that combining the Future Aviation Safety Team (FAST) methodology with the Causal model for Air Transport Safety (CATS), initially developed for the Dutch government, if combined with implementation measures, provides the best way forward towards realizing such a safety method.

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Acronyms

Acronym	Definition
ACFT	Aircraft
AMC	Acceptable Means of Compliance
ANS	Air Navigation Service
ANSP	Air Navigation Service Provider
AoC	Area of Change
ARP	Aerospace Recommended Practice
ASRS	Aviation Safety Reporting System
ASCOS	Aviation Safety and Certification of new Operations and Systems
ATC	Air Traffic Control
ATM	Air Traffic Management
CAST	Commercial Aviation Safety Team
CATS	Causal model for Air Transport Safety
EASA	European Aviation Safety Agency
ESARR	EUROCONTROL Safety Regulatory Requirements
EHAM	Amsterdam Schiphol Airport
E-OCVM	European Operational Concept Validation Methodology
ESD	Event Sequence Diagram
ESSI	European Strategic Safety Initiative
FAA	Federal Aviation Administration
FAST	Future Aviation Safety Team
FCL	Flight Crew Licencing
FDM	Flight Data Monitoring
FHA	Functional Hazard Analysis
FMECA	Failure Mode Effects and Criticality Analysis
FOQA	Flight Operations Quality Assurance
HAZOP	HAZard and OPerability study
HTRR	Hazard Tracking & Risk Resolution
IFPS	Integrated Initial Flight Plan Processing System

Acronym	Definition
JPM	Jean-Pierre Magny
LCC	LCC (Life Cycle Costs)
LEMD	Madrid Barajas Airport
MRO	Maintenance Repair Overhaul
NLR	National Aerospace Laboratory of the Netherlands
PDARS	Performance Data Analysis and Reporting System
PIC	Pilot In Command
QAR	Quick Access Recorder
R&D	Research and Development
SAM	Safety Assessment Methodology
SADT	Structure Analysis and Design Technique
SB	Service Bulletin
SMS	Safety Management System
SRC	Safety Regulation Committee
TAS	Total Aviation System
TCAS	Traffic Collision Avoidance System
TO	Take Off
TOPAZ	Traffic Organization and Perturbation Analyzer
TOWS	Take Off Warning System
TSB	Transportation Safety Board
WP	Work Package

Executive Summary

This study supports the development of a complete safety assurance process within the total aviation system. It is concluded that proposed safety assessment methods should:

- Address the 'Total Aviation System';
- Provide means to address interfaces and interactions between different aviation system domains;
- Address current and future risks;
- Anticipate detection of emerging risks and precursors in early program phases;
- Be appropriate for supporting the certification process;
- Address all lifecycle phases;
- Satisfy stakeholder's needs, obviously aiming to reach a high level safety in a cost effective manner.
- Make use of more integrated supporting tools for safety assessment

Risk and safety management shall be a seamless process throughout programs' life cycle within and between all aviation domains. Rather than developing a new method from scratch, existing methods are evaluated in order to identify promising (combination of) methods that meet the above requirements and can be embedded in a certification scheme tied up to engineering safety analysis. This justifies selection of:

- Causal Model of Air Transport Safety (CATS) [14, 15], promoting the prevention of aircraft accidents through better understanding of aviation risks in terms of causes and magnitude.
- Future Aviation Safety Team (FAST) methodology (FAST/EME1.1 [7, 8, permitting to identify and take care of future and emerging risks.
- Program management dispositions, without which it may be difficult to follow a total system approach and systematically apply safety analysis, risks mitigations and proper decision making.

A. Existing know how

Existing safety methods identified represent the common denominator of methods applicable to the various aviation domains. All identified safety methods should be capable to incorporate inputs (e.g. emerging risks) from the FAST/EME1.1 process, to perform safety analysis of any system and systems of systems (total system), airborne or not, organisation and management permitting their implementation. For proper decision making, safety culture needs to be widely spread out at all hierarchy levels. FAST (Future Aviation Safety Team) has the unique capacity to bring more anticipation to safety and engineering as an augmentation process of existing practices without dramatic changes.

B. Precursors detection

Most organisations are already using processes dealing to some extent with so-called precursors but not implemented to ensure a reliable precursor's detection. Precursors detection and mitigation program concerns all life cycle phases, but with highest emphasis on early design phases. A generic process flow for identifying, evaluation, and handling of precursors is defined.

C. Emerging risks

The Future Aviation Safety Team (FAST) methodology, endorsed by EASA under the European Aviation Safety plan (EASp) action EME 1.1, has identified and maintains a repository of Areas of Change (AoC) [8] that:

- Provides all actors during the entire life cycle with a wide scope list of emerging risks;
- Allows providing design and certification justification of systems robustness to new risks;
- Is suited to enrich the analysis and efficacy of risk control measures and clarifies whether or not safety enhancements resist to emerging risks [7].

It is shown that about 10 years ago, the FAST identified emerging risks associated to major changes that would permit to predict events scenarios leading to recent accidents. Using the FAST methodology and its outputs (e.g. Areas of Change) as an input to a system wide safety assessment and using its capacity to bring more anticipation to most safety processes, is of paramount importance for the near and far future.

D. Safety assessment methodology

ASCOS WP3 is developing safety based design methods and tools that enable handling of current, future and emerging risks. The proposed combination of methods (CATS and FAST/EME1.1) address the Total Aviation System, and are expected to support derivation of Safety Objectives and Safety Requirements for any proposed change within the TAS (e.g. new technologies, operations, systems and/or products).

E. Certification

A safety assurance process totally integrated in all program disciplines is the core of the proposed improvement strategy. Updated design justification documents incorporating all safety analysis are considered here as bringing fundamental benefits in the certification process. In follow-up activities, further efforts should be dedicated to incorporation of the identified safety methods and supporting process flow for identifying, evaluation, and handling of precursors in the ASCOS Outline proposed certification approach [26].

F. Recommendations

Methodologies and fields of application

- Safety methods should be published as part of safety training material at any organisation level.
- Safety assessment results should be made available to all engineering and decision making levels.
- A total aviation system approach, as followed in the Causal model for Air Transport Safety (CATS), with its capacity to bring a better perception of all possible accident and accident avoidance scenarios is showing benefits and is recommended to be integrated within safety methods and processes.
- Safety methods should be an explicit part of the early phases of program management and promoted accordingly, so as to devote more safety effort in early program phases, in combination with engineering and certification, the latter considered as direct product from design justifications.

Precursors

- Identifying precursors and emerging risks is important in safety assessment processes. Precursors detection methods are recommended to become part of a standard or, at least, a handbook.

- Precursors' detection and organisation dispositions should be part Integrated Logistics Support (ILS) dispositions as defined at program's level.
- Improved detection of precursors can play a significant role in enhancing continuous safety monitoring activities.

Standardization

- Promote the creation and/or updates of standards towards a total aviation system safety approach.
- Encourage participation to the SAE S18 and/or EUROCAE Working Group 63, permitting to upgrade the EUROCAE and SAE ARP standards accordingly, with the methods and tools developed in ASCOS.

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1 Introduction

1.1 Background and scope

Fundamental changes in the institutional arrangements for aviation regulation in Europe, the introduction of new technologies and operations, and demands for higher levels of safety performance call for the adaptation of existing certification processes. The European Commission (EC) Project 'Aviation Safety and Certification of new Operations and Systems' (ASCOS) contributes to the removal of certification obstacles and supports implementation of technologies to reach the EU ACARE Vision 2020 [21, 22, 23] and Flight Path 2050 [24] goals. ASCOS outlines a newly proposed approach to certification that [25, 26]:

- Is more flexible with regard to the introduction of new operations, systems and products;
- Is more efficient, in terms of cost, time and safety, than the current certification processes;
- Considers the impact on safety of all elements of the total aviation system and the entire system life-cycle in a complete and integrated way.

Moving towards performance based regulation, based upon agreed safety performance in combination with risk based approach to standardization, is expected to lead to improvements in the way that safety risks are controlled [25, 26]. Anticipating on future risks and hazards by using a "proactive approach" helps to make the certification process robust to new developments. Introducing 'continuous safety monitoring' will ensure that new and essential safety data is effectively used immediately after it will be available.

Promising options for adaptations of the existing certification processes include [26]: 'change between performance-based and compliance-based or vice versa', 'proof of concept approach', 'enforce existing rules and improve existing processes', and 'cross-domain fertilization'. Introducing certification process adaptations cannot be done without giving due account to safety considerations: each of these options requires evidence on safety assurance as key element in a certification process. The need for safety improvement is also recognized in the ACARE Beyond Vision 2020 (Towards 2050) [23], which states that 'society is increasingly reluctant to accept failures in the Air Transport System, which exerts more pressure on safety considerations'. The Flightpath 2050 Vision for Aviation [24] specifically aims for a *holistic, total system approach to aviation safety, integrated across all components and stakeholders. This will be supported by new safety management, safety assurance and certification techniques that account for all system developments. Just culture will be adopted as essential element of the safety process* [24]. Clearly, there is a need for new safety based design systems and supporting tools that address the *total aviation system*, while being able to anticipate on *future and emerging risks* that may exist in a future aviation system that will differ from today's aviation system.

Although a total aviation system approach is becoming more widely supported in aviation, there is still a lot to be done before this will actually be embedded in certification processes and safety management. Safety topics that require further research – in particular from a total aviation system point of view – are e.g. development of a framework of Safety Performance Indicators, establishment of a baseline risk picture and safety performance targets, definition of a process for continuous safety monitoring, development of risk models and accident scenarios representing the future aviation system, and subsequent incorporation of the – total aviation system – safety methods and tools in safety standards (and certification processes).

The current certification regulations in aviation, still considered as the end milestones of a safety assurance process totally integrated in all program disciplines, are basically reactive in the sense that changes in certification requirements are often made as a reaction to major accidents or as a reaction to technological advances. New safety regulatory requirements may become effective many years after occurrence of an accident, when new technological developments are already commonplace. A consequence of the delay in implementation of the necessary regulatory changes is that original design assumptions may have become invalid, because e.g. the operational environment, aircraft systems, and ATM infrastructure may have evolved significantly. Newly employed operations and/or systems may bear emerging risks and future potential hazards that are unknown today. Therefore, it will be necessary to reaffirm the original safety objective of certification, identify the need to adapt to new environment possibly different operations, and to develop a safety picture of the future, taking into account likely changes, trends as well as the introduction of new products, systems, technologies and operations for which safety regulations may need to be updated. Anticipating on such future 'emerging risks' and potential hazards by using a 'proactive approach' will help to make the certification process robust to such new developments.

Addressing certification means also sorting out all design activities that have to provide justifications for certification acceptance. This includes not only existing certification regulations originally related to safe design of possibly outdated function, but the verification of applicability to any specific system or element placed in any foreseeable conditions. This verification requires methods and their implementation. The aviation system can be regarded as a large system composed of several elements. Aviation safety research has shown that the ability to communicate and cooperate between different disciplines of the aviation is vital for the aviation system safety performance. Safety depends on the elements and on the interfaces between the elements; it is the weakest link in the chain that determines safety performance. Therefore, a new approach towards certification – that considers the impact on safety of all elements of the aviation system and the entire system life-cycle in a complete and integrated way – will be beneficial for further safety improvement. In the early development stages of a newly proposed system and/or operation, an improved safety assessment method (and associated supporting safety based design systems or tools) could provide the means to deal better with the above sketched difficulties.

1.2 Objectives

Within aviation, a wide variety of safety assessment methods is available. There are many similarities and redundancies but often these methods are focusing on one specific domain or on one specific part of the life-cycle of an operation system. From a safety and cost benefit perspective, it will be a significant advantage if safety methods (and supporting tools) can be used in the different domains, be able to address changes all along program's life cycle, from early design phases to operations, and support continuous safety monitoring, be fully coordinated within management activities. It is therefore necessary:

- To perform a synthesis of existing know how on (predictive) risk identification methods;
- To develop an advanced process for the identification of precursors of (emerging) risks;
- To develop a list of emerging risks, and propose a procedure for continuously updating this list;
- To support the ASCOS proposed certification approach with appropriate safety methods.

1.3 Approach

The initial idea is to combine the FAST methodology (endorsed by EASA as FAST/EME1.1 methodology [7]) with the quantitative safety method used in the Causal model for Air Transport Safety (CATS) [14, 15], which covers all possible types of accidents in the total aviation system. The Future Aviation Safety Team (FAST) was constituted under the European Commercial Aviation Safety Team (ECAST). FAST developed an approach to discovering aviation futures which uses the concept of 'Areas of Change', considering that several possible futures might interact with the future under study, producing unanticipated hazards. The approach is to bring this approach to a next level by considering the concept of 'areas of change' in a certification framework. FAST is able to provide risks pictures of the future to all program phases to any safety, engineering and program actor in all aviation systems and at the end to certification.

However, improvements and more detailed guidance material for these safety methods may become necessary, when needs and criteria are better defined. The different steps to be taken are as follows.

First, the needs and selection criteria for a total aviation system safety assessment methodology will be defined. Promising (already existing) safety methods – that may be used as building blocks – will be identified. Next, existing methods for detection of precursors of risks will be evaluated and an improved process for identification of precursors for future and emerging risks will be defined. This is followed by updating an existing repository of "Areas of Change", which was developed by the FAST, and which enables the identification of emerging risks and associated hazards. A process for continuous updating of the repository of "Areas of Change" and a list of emerging risks is proposed. Finally, recommendations and guidance is provided.

1.4 Structure of the document

Section 2 provides a synthesis of existing know- how on safety methods, including the identification of needs and criteria for a total aviation system safety assessment methodology. Section 3 describes an improved process for identification of precursors of emerging and future risks. Section 4 develops the list of Areas of Change and associated emerging risks. The conclusions and recommendations are given in Section 5.

2 Synthesis of existing know-how

2.1 Introduction and study logic

Having defined where and how to improve safety analysis, it becomes necessary to evaluate the capability of existing safety assessment methodologies and their capability to contribute to the expected Safety Improvement. Experience gained with the FAST, European Strategic Safety Initiative (ESSI), connections with the Commercial Aviation Safety Team (CAST) and NLR data base, provides an exhaustive list of methodologies. FAST has subjected its wide list to a ranking process ending up in a short list of methods capable of proactive safety [7, 8].

This list has now to be further evaluated against the possibility to be applied in the various components of the Total Aviation System (Aircraft, Airframe, Board Systems, ATC/ATM, Airlines, MRO, etc.). Already operational methods in these domains have to be identified and considered as primary target for enhancement. As well as methods identified in standards, whose application is already in progress or planned (ARPs, SAM), have to be added to the list of potential, possibly preferred candidates.

Another criterion to be identified is the capability of these methods to find their place in program phases, right from early design, (not only for each component but also for the total aviation system). This requires looking at the application of safety assessment techniques within programs' management methods, tasks and standards.

Within aviation's continuously changing environment, safety assessment should take care of evolutions and transitions phases (e.g. aircraft at various standards flying in airspaces sectors that are not all at the same standard, with pilots switching between various aircrafts, makes and versions). A particular attention has to be paid to the huge number of failure scenarios that may emerge during the long life cycle of aircraft and other aviation systems. Systems may be operated differently than initially designed for.
We should also address weaknesses that may concern safety barriers, otherwise said, to identify where and when in the life cycle of a system, safety barriers fail or lose efficiency. Safety barriers initially supposed to remain valid for the entire system's life may be eroded over decades or due to changes in operational assumptions.

2.2 Identification of needs and selection criteria

This section aims to identify the needs of a Total Aviation System (TAS) safety assessment methodology. These needs also aim to serve as criteria for selecting appropriate methods for the methodology. The needs are identified by reviewing sources on candidate needs, and by consecutive consolidation. The primary sources reviewed are the ASCOS Description of Work [1], an existing review of SESAR-identified needs [13], and input from the contributing partners. The table below provides an overview of the resulting needs. Next, each need is described in more detail.

Table 1 Overview of needs

Overview of needs	
A.	The methodology has to address the Total Aviation System (TAS) and to provide the means to address all the interfaces and the interactions between the different aviation system domains
B.	The methodology should make use of more integrated supporting tools for safety assessment
C.	The methodology has to address current and future risks
D.	The methodology has to be appropriate for supporting the certification process developed in WP1
E.	The methodology has to address all lifecycle phases
F.	The methodology has to be appropriate for developing safety assessments of good quality
G.	The methodology has to make use of inputs from experts with appropriate qualifications
H.	The methodology should adopt stakeholders' wishes

The words 'has to' and 'should' are used to distinguish between the priority of these needs:

- 'has to' refers to something that is required.
- 'should' refers to something that is preferred.

A. The methodology has to address the total aviation system and to provide the means to address all the interfaces and the interactions between the different aviation system domains

The methodology to be developed has to address the TAS. This does not mean that there must be a monolithic methodology that addresses each element of the TAS in an identical way. Rather, it means that the methodology addresses each element, and all associated interfaces and interactions. This includes several domains (e.g. ATM/ANS, aircraft/airworthiness, flight operations and Flight Crew Licensing (FCL), and aerodromes), several system element types (hardware, software, procedures, humans, organizations), the different geographic and cultural origins of the elements, and the associated interfaces and interactions. An additional recommendation is to identify compatibility with existing practices in the various domains, compatibility considered as the capability to incorporate proposed upgrades without creating a revolution that would not be accepted. That also means that implementation of the methodology would possibly requires management dispositions permitting a seamless safety assessment, taking care on any event interacting through any internal or external interface with capacity to mitigate corresponding, risk right from its emergence in early program phases in all systems or subsystems concerned.

B. The methodology should make use of more integrated supporting tools for safety assessment

Whereas the methodology does not need to address each element of the TAS in an identical way, it is desirable that it makes use of integrated supporting tools. The aim of this is to contribute to a more efficient process, and a better safety assurance of the interactions between elements. Where required for a sufficiently reliable safety assessment, it must remain possible that the methodology uses different techniques for analysis of different elements or domains.

C. The methodology has to address current and future risks

The methodology has to address all relevant risks of the future operation or system. This includes risks already present in the operation, and risks that arise or may arise after implementation. To which extent certification requires comprehensive analysis of possible future changes in the environment of the operation as considered in FAST, is to be evaluated and introduced in systems' requirements. As proposed here, identification of future changes is the first necessary step followed by ranking and tailoring to program objectives.

A specific point of attention is the emerging risks to be addressed. Many definitions exist of emergence and of emerging risk. This study uses the following definitions:

> An "emerging risk" is defined as a familiar risk that is increasing or a new risk that becomes apparent in new or unfamiliar conditions (derived from IRGC [10]). Familiar risks here refer to the current/known risks that are identified and accepted during the certification process.
>
> Emerging risk can be:
>
> - A current/known risk with the same Severity but with a different Likelihood of its components taking into account the influence of new technologies, behaviours, work organizations, regulations, operational procedures etc.,
> - A current/known risk with a new Severity and the same Likelihood of its components,
> - A current/known risk with a new Severity and a new Likelihood of its components.
> - A new risk resulting from the interactions of multiple contributors that may have not been fully anticipated, in an environment in evolution.

D. The methodology shall be appropriate for supporting the certification process developed in WP1

The main objective of ASCOS is to propose a novel certification approach with supporting safety assessment methodology. Accordingly, the methodology has to be appropriate for supporting the ASCOS outline proposed certification approach [26].

E. The methodology shall address all lifecycle phases

Certification processes often start when the product to be certified is already relatively mature, many design decisions are however taken in an earlier phase. For such developments early feedback on design options is required regarding bottlenecks in safety and other key performance areas. The methodology to be developed shall accordingly address all lifecycle phases, including these important early phases.

F. The methodology shall be appropriate for developing safety assessments of good quality

In order to contribute to safer operations and systems, the results of safety assessments shall be of sufficient reliability. To ensure this, the methodology shall satisfy basic quality requirements applicable to safety assessments. To evaluate this, use may be made of the safety validation quality indicators available from EUROCONTROL SRC's [5]. These indicators were developed for application to safety validation of (major) changes in air transport operations, but may be generalised for use across the total aviation system.

G. The methodology shall make use of inputs from experts with appropriate qualifications

In aircraft airworthiness certification, use is made of test pilots with specific qualifications for performing these duties. These qualifications go significantly beyond those of most commercial pilots. Within the ATM domain, however many safety assessments use input from air traffic controllers and/ or pilots who do not have specific certification qualifications. For sufficiently reliable safety assessment results, it is of importance that experts have appropriate qualifications.

H. The methodology should adopt stakeholders' wishes

It would be beneficial if the methodology satisfies stakeholders' wishes, since then stakeholders would be more likely to adopt it. As an important example for this, if the methodology augments what is done presently, then there is a larger chance of the methodology being broadly applied (evolution, not revolution). All types of stakeholders are relevant, including authorities.

2.3 Identification of promising safety methods

Safety assessment methods have been developed over a number of years in a variety of different branches of industry. There is an enormous variety of risk assessment conceptual frameworks, methodologies, and methodologies catalogues. Three catalogues of safety methods that exist are:

- Safety assessment methods database [12]. This document gives an overview of about 800 techniques, methods, databases, and/or models that can be used during a Safety Assessment. Besides a summary of the aim, description, domain (e.g. nuclear, chemical, air traffic management, aviation, aircraft development, computer processes), application (i.e. applicable to hardware, software, human, procedures, or to organisation) of the method, it describes for which safety assessment stage (i.e. scope the assessment, learning the nominal operation, identify hazards, combine hazards into risk framework, evaluate risk, identify potential mitigating measure to reduce risk, safety monitoring and verification, and/or learning from safety feedback) a particular safety method could be used.
- ATM safety techniques and toolbox [6]. This document comprises 27 techniques that can be used to evaluate and improve safety in ATM. It outlines a simplified eight-stage safety assessment approach and then provides details about the safety assessment techniques. It explains where the technique comes from, its maturity and life cycle stage applicability, the process and data requirements, and practical and theoretical advantages and disadvantages. The overall approach biased towards concept design and development, but most of the techniques can also be applied to existing systems.
- Guide to methods and tools for airline flight safety analysis [20]. This document provides summaries of 57 methods and tools that can be used to analyse flight safety data including event reports and digital flight data. These methods and tools are organized into three areas: flight safety event reporting and analysis systems, flight data monitoring analysis tools, and specific purpose analytical tools.

As a result of a joint initiative by the FAA and EUROCONTROL, a committee of experts (the AP15 group) has evaluated more than 500 techniques. The impression that there are huge difference between the methods applied in the aircraft and ATM domain seems to be not correct. Most safety assurance analysis techniques apply the same basic principles but are often referenced under different names and structures or combine several analysis. This resulted in a list of 27 selected techniques in the context of safety management process [6]. The safety assessment of an air traffic operation has been presented as a seven-stage process, as shown below, that revealed to be in line with any system and system of systems safety assessment:

Table 2 Generalised eight stages safety assessment process [6]

	Name of stage	Outputs	Techniques
1.	Scope the Assessment	Safety plan; assignment of safety/risk criteria (e.g., Target Level of Safety (TLS))	Scoping does not always use defined techniques, and may be informed by assessor judgment and incident/accident experience, and prior practice in a related area. The approach will depend on local adaptation and the organization's Safety Management System (SMS). The FAST methodology helps scope the assessment by defining Areas of Change in the Concept of Operation.
2.	Modeling the nominal operation	Description of operations and systems used.	Hierarchical Task Analysis, TOPAZ accident risk assessment methodology, and SADT. Additionally a number of other system modeling techniques exist, but these vary in usage in ATM, and ATM is in fact still exploring best techniques to use. This area will therefore be redressed in later versions of this report.
3	Identify hazards	Defined hazard set	Air Safety Database, ASRS, Common Cause Analysis; External Events Analysis; FAST; FMECA; HAZOP; Human Factors Case; TOPAZ accident risk assessment methodology; TRACER-Lite, PDARS
4	Combine hazards into a risk framework	Risk Model	Bow-Tie; Collision Risk Models; Common Cause Analysis; Event trees; Fault trees; Human Performance Simulation; TOPAZ accident risk assessment methodology.
5	Evaluate Risk	Evaluated Risk Model; identify and evaluate dependencies, evaluation of risk against target criteria; risk-informed decision-making becomes possible	ASRS; Human Error Database; Bias and Uncertainty Assessment; Collision Risk Models; Common Cause Analysis, FAST; TOPAZ accident risk assessment methodology; HEART.
6	Identify potential mitigating measures to reduce risk	Potential mitigating measures to reduce risk	HAZOP; Human Factors Case; TRACER-Lite; HTRR, Bow-Tie, TOPAZ accident risk assessment methodology. SAE ARP 5150
7	Confirm actual risk is tolerable or reducing	Measurement of safety-related events & data against predictions	ASRS, PDARS, Air Safety Database, FOQA, FDM.
8	Organizational Learning through feedback	Better knowledge in operations, safety assessment and design concerning how to manage safety effectively in ATM.	ASRS, ASAP, PDARS, FOQA, FDM, Air Safety Database; HTRR. PLADS, GATE, Morning Report

Note: The above 8 steps table is suited for and applied in the operational phase. It corresponds in the aircraft domain to what is standardised in SAE ARP 5150 "Safety Assessment of Transport Airplanes in Commercial Service" [18]. Application to aircrafts development phase is standardised in SAE ARP 4754/EUROCAE ED 79A "Guidelines for Development of Civil Aircraft and Systems" [16], which logic looks applicable to other systems.

The following table presents selected methods and how each fits into the 8-stage framework [4]:

Table 3 Methods usable for future safety assessment

Future safety analysis technique	Framework steps							
	1	2	3	4	5	6	7	8
ASRM (Aviation Safety Risk Model)				x	x			
Bias and Uncertainty Assessment					x	x		
Bow-Tie Analysis				x	x	x		
BBN (Bayesian Belief Networks				x				
CATS (Causal model for Air Transport safety)	x							X
CapSA (Capability Safety Assessment (CapSA)		x		x	x	x		
CIA (Cross Impact Analysis)				x	x			
CSA (Comparative Safety Assessment)					x	x		
CCA (Common Cause Analysis)			x					
DBN (Dynamic Bayesian Network)				x				
DYLAM (Dynamic Logical Analytical Methodology)				x				
Data Mining			x		x		x	x
ERM (Emerging Risks Methodology)			x					
External Events Analysis				x	x			
ETA (Event Tree Analysis)				x				
FAST Method (Future Aviation Safety Team)	X	x	x					
FHA (Functional Hazard Assessment)			x					
FOQA (Flight Operational Quality Assurance)		x			x	x	x	x
FORAS				x	x	?		
FMECA (Failure Modes Effects and Criticality Analysis)			x		x			
FRAM (Functional Resonance Accident Model)				x				
Gael Risk Analysis	X	x	x	x	x	x	x	x
HAZOP (Hazard and Operability study)			x					
HRA (Human Reliability Assessment)				x	x	x		
HAMECA (for human related hazards)			x		x			
IRP (Integrated Risk Picture)		x	x	x	x			
Multi-Agent Dynamic Risk Modelling	X	x	x	x	x	x		x
MASCA (Managing System Change in Aviation)								x
Monte Carlo Simulation Analysis		x	x	x	x	x		
NextGen Future Safety Assessment Game				x	x			
PHA (Preliminary Hazard Analysis)			x					
Pure Hazard Brainstorming			x					
PRA (Probabilistic Risk Assessment based on FTA/ETA)				x	x			
Petri Nets				x				
PSSA (Preliminary System Safety Assessment)				x	x	x		
Quantification of systemic risk and stability					x			
Reliability Growth Modelling						x	x	x
Risk AHP method					x			

Future safety analysis technique	Framework steps							
	1	2	3	4	5	6	7	8
Root Cause (Event Tree) Analysis				x		x	x	x
Scenario Analysis	X		x		x			
SAFMAC (SAFety validation framework for MAjor Changes)	X							
Sensitivity Analysis		x	X	X	X	x		x
SRM "SESAR Safety Reference Material",	X	X	X	X	X	X	X	x
STAMP (Systems Theoretic Accident Modelling and Process)			x		x	x		x
SOCRATES (Socio-Organisational Contribution to Risk Assessment and the Technical Evaluation of Systems)				x				
TRIAD Tool for Risk Identification, Assessment, and Display (TRIAD)			x	x	x	x	x	?
Weibull Analysis			X		X	X	x	

In response to a request from EASA, Future Aviation Safety Team (FAST) conducted a review of safety risk analysis methods, in order to devise a methodology to assess (as well as anticipating and mitigating) future risks [7]. Criteria to rate about 30 identified applicable methods, according to its ability to provide insight into the future hazard/risk identification objectives, have been developed and applied. The resulting FAST/EME1.1 method, which describes a proposed process of carrying out a future risk assessment, is initially targeted at commercial entities and governmental organizations. Nevertheless, application to newly proposed changes (e.g. operations, systems, products, processes) in the aviation system seems also possible. The FAST method is built on three critical elements: a credible depiction of the future, a description of scenarios that will result in a number of hazards by looking forward in time, and a set of tools to execute the risk analysis that will produce credible results (while using e.g. credible data, addressing human factors influences).

The FAST Method is aimed at identifying future hazards that have not yet appeared because the changes within the aviation system that may produce these hazards have not yet taken place. The method process flow consists of 12 steps; 1) Be responsible for implementation of global aviation system changes; recognize your need for systematic prediction of hazards associated with changes and to design those hazards out of the system or avoid or mitigate the hazard; 2) Clearly define scope of expert team study; 3) Assemble an expert team; 4), 5) and 6) Communicate with FAST and Customer to understand the complete task; to understand pertinent Areas of Change (AoC); to determine key interactions; 7) Refine the visions of the future; 8) Compile the hazards; 9) Determine the watch items; 10) Compile recommendations; 11) Inform FAST regarding results; 12) Inform customers regarding results. The FAST method introduces safety assessment of a scoped future system in its future context, using a scenario-based approach and enriched safety assessment methodology.

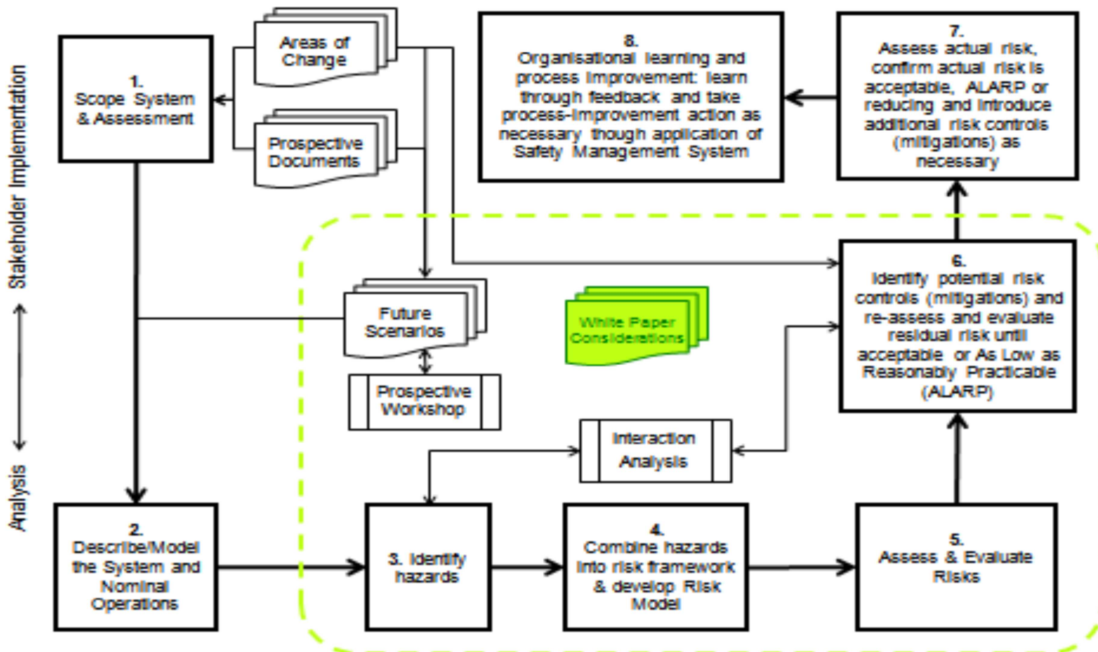

Figure 1 Future Aviation Safety Team (FAST) methodology

Examples of accident sequence models are the Integrated Risk Picture (IRP) of Eurocontrol [27] and the Causal Model for Air Transport Safety (CATS) of the Dutch Civil Aviation Authority [14]. These models are based on phenomenological knowledge and operational experience and are quantified with operational performance data and expert judgement. Event sequence models like IRP and CATS can be used to integrate information on all available safety performance indicators into a single risk picture, are predominantly constructed of active failure events, and do not contain many latent failure events. The fact that accident sequence models are mainly quantified from (past) operational data means that event sequence models are a source of lagging indicators as they capture failure results from a past time period and characterise historical performance.

The ASCOS accident model is based on previous accident model development work, primarily the work performed to create the Causal Model for Air Transport Safety (CATS) [14]. CATS has been developed for the Dutch Ministry of Transport and represents the total aviation system. For the purpose of the ASCOS accident model some qualitative changes have been made to the CATS ESDs to incorporate the lessons-learnt of the last couple of years in which CATS has been used and studied. These changes include different naming of events, different definitions, addition or deletion of events, and combining of ESDs. An overview of differences between the CATS ESDs and the ASCOS ESDs is presented in ASCOS D3.2 [15]. The CATS model characterizes all historical commercial air transport accidents. A comparison of the updated CATS with the EASp main operational issues [15] shows that the five operational issues cover the majority of the CATS scenarios. The initiating events for the ESDs representing the updated CATS scenarios are shown in Table 4 [15].

Table 4 Initiating events for the accident scenarios in the ASCOS risk model [15]

ESD[1]	**Initiating event**
1	Aircraft system failure during take-off
2	ATC related event during take-off
3	Aircraft directional control by flight crew inappropriate during take-off
4	Aircraft directional control related systems failure during take-off
5	Incorrect configuration during take-off
6	Aircraft takes off with contaminated wing
8	Aircraft encounters windshear after rotation
9	Single engine failure during take-off
10	Pitch control problem during take-off
11	Fire, smoke, fumes on-board aircraft
12	Flight crew member spatially disorientated
13	Flight control system failure
14	Flight crew incapacitation
15	Ice accretion on aircraft in flight
16	Airspeed, altitude or attitude display failure in flight
17	Aircraft encounters thunderstorm, turbulence or wake vortex
18	Single engine failure in flight
19	Unstable approach
21	Aircraft weight and balance outside limits during approach
23	Aircraft encounters windshear during approach/landing
25	Aircraft handling by flight crew inappropriate during flare
26	Aircraft handling by flight crew inappropriate during landing roll
27	Aircraft directional control related systems failure during landing roll
31	Aircraft are positioned on collision course in flight
32	Runway incursion
33	Cracks in aircraft pressure cabin
35	TAWS alert
36	Conflict on taxiway or apron
38	Loss of control due to poor airmanship

[1] The ESD numbering does not run continuously as a result of several development cycles during which some scenarios were combined. The original numbering was kept intact for better configuration control of the model.

The ASCOS project team is aware of the development of the SESAR Accident-Incident Model (AIM) [28, 29, 30] and its predecessor the Integrated Risk Picture (IRP) [27]. Similar to the CATS model and the IRP, the SESAR AIM consists of a risk model, which shows the risks of aviation accidents and provides a structured breakdown of their causes, with particular emphasis on ATM contributions (both positive and negative). Using the AIM, a risk picture for SESAR is being developed to represent the combined effects of the set ATM changes that are expected to be in place by 2013, 2017 and 2020. Each ATM change is modelled through adjustments representing its expected impacts on appropriate elements of the risk model. These effects, together with the effects of changes in traffic levels, can then be summed to estimate the total risks and contributory / causal breakdown for 2013, 2017 and 2020. This approach allows investigation of the improvements that are necessary to satisfy the ECAC wide safety targets. However, a Risk Picture for SESAR is still under development.

The ASCOS accident model and AIM are comparable; they both consist of event sequences detailed with fault trees. AIM focuses on 6 ATM-related accident scenarios. The ASCOS accident model on the other hand covers the total aviation system, and therefore also includes non-ATM-related accident scenarios. AIM does have more detailed fault trees. Because the focus of ASCOS is on the total aviation system, it cannot make use of AIM (only), and therefore needs an accident model that covers the total system. If more detailed fault trees are needed within the scope of ASCOS, suitable fault tree elements from AIM can be adopted if the latter model is fully developed. Note that ASCOS has developed a baseline risk picture for the total aviation system [11]. If the changes within the total aviation system that are expected to be in place in the future (e.g. as foreseen within the EC strategies reflected in the Vision 2020 or Flight Path 2050) are properly modelled, it is possible to estimate the risks for all the accident scenarios that are affected by the change. Subsequently, it is possible to investigate improvements needed to satisfy certain (pre-defined) safety performance targets.

The following short list of methods included in EUROCAE WG-63 and SAE/ARP standards provides further basic methods that appear to be sufficient to be the backbone of most other safety methods.

- Functional Hazard Assessment (FHA)
- Preliminary System Safety Assessment (PSSA)
- System Safety Assessment (SSA)
- Fault Tree Analysis
- Dependence Diagram/Markov Analysis
- Failure Modes and Effects Analysis (FMEA)
- Failure Modes and Effects Summary (FMES)
- Common Cause Analysis (CCA) Zonal Safety Analysis (ZSA)
- Particular Risks Analysis (PRA)
- Common Mode Analysis (CMA)

All of these methods appear to be capable to incorporate most advanced thinking inputs (e.g. emerging risks) from the FAST/EME1.1 process. All are capable to perform safety analysis of any system and systems of systems, airborne or not. A detailed description of each is available in appendices of the EUROCAE ED135 / SAE standard ARP4761 [17].

2.4 Discussion

A number of methods has been identified and evaluated against needs and selection criteria.. A combination of tools and methods is necessary to achieve key safety objectives, but the list of those considered as necessary and candidates for application in all aviation domains appears limited. Almost everything exist, like bricks in a wall or instruments in an orchestra, the key condition for success lies in implementation conditions, tied up to program management (1) and organisation. Moreover between operations and engineering there should be a continuous link. Engineering has to continuously learn from field experience. Operations need support from designers, to analyse any event and keep up airworthiness on a seamless manner. It is a fundamental condition for safety. On top of that, for proper decision making, safety culture needs to be widely spread out at all hierarchy levels with high emphasis on very low probability possibly high severity events. A permanently upgraded list of emerging risks coming from the Future Aviation Safety Team provides all methods with additional longer term vision and decision making justifications. FAST has the unique capacity to bring more anticipation to most safety and engineering processes. It is an augmentation process of existing practices that doesn't require dramatic changes.

A combination of safety methods and tools will likely be necessary is necessary to achieve key safety objectives. The idea is to combine the FAST methodology (endorsed by EASA as FAST/EME1.1 methodology [7]) with the quantitative safety method used in the Causal model for Air Transport Safety (CATS) [14, 15], which covers all possible types of accidents in the total aviation system. FAST developed an approach to discovering aviation futures which uses the concept of 'Areas of Change', considering that several possible futures might interact with the future under study, producing unanticipated hazards. The approach is to bring this approach to a next level by considering the concept of 'areas of change' in a certification framework. FAST is able to provide risks pictures of the future to all program phases to any safety, engineering and program actor in all aviation systems and at the end to certification. Therefore, a logical step forward is to investigate if and how the FAST and CATS methods may be incorporate into safety standards developed by EUROCAE/SAE.

3 Process for identification of precursors for future and emerging risks

3.1 Introduction and study logic

The Aviation Safety Teams (organization elements performing safety assessment in any aviation domains) are attempting to identify what can go wrong in the aviation system and are looking for mitigating measures. Precursors (as defined in the next paragraph) appear to be of high importance in accidents prevention. It is our experience in many accidents investigation that precursors of the accident were present but were not acted upon.

This document addresses:

- The Total Aviation System, therefore taking care of events generated and propagating from one system to the others.
- Scenarios where a presumably classified minor event may become the additional contributor in a sequence ending up in accidents.
- In the near or far future on-going changes (e.g. new technologies increasing complexity of organizations) may create gaps in safety processes or generate new risks. FAST has also identified possible interaction between categories of changes (e.g. environmental, societal) that may generate complex events sequences.
- The whole “life cycle” therefore, precursors can be found in any phase, concept, preliminary design, production, and operations. All available precursors complete accidents scenarios and corresponding risk assessment.

3.2 Definitions

A precursor is defined as an "identifiable event that may be used as early warning for known or potential hazards". Such early warnings may be:

- Events identified and currently monitored, for which the potential to become hazardous is known to be significant
- Events known yet, but for which induced risks may have been initially underestimated therefore not enough reduced, neglected or even unidentified up till now, unless revealed by an actual occurrence of the hazard

A systematic precursor’s capture process is an efficient means for enhancing and maintaining risk awareness and for proactive identification of needed safety actions.

A "current/known risk" is defined by its severity and the current/known likelihood of occurrence.

An "emerging risk" is defined as a familiar risk that is increasing or a new risk that becomes apparent in new or unfamiliar conditions (derived from IRGC [10]). Familiar risks here refer to the current/known risks that are identified and accepted during the certification process. Emerging risk can be:

a) A current/known risk with the same Severity but with a different likelihood of its components taking into account the influence of new technologies, behaviours, work organizations, regulations, operational procedures etc.
b) A current/known risk with a new severity and the same likelihood of its components.
c) A current/known risk with a new severity and a new likelihood of its components.
d) A new risk resulting from the interactions of multiple contributors that may have not been fully anticipated, in an environment in evolution.

A "future risk" is defined as a risk associated with the future introduction of a novelty (e.g. new design, new procedure, and new organization).

In ASCOS we consider current/known risks as well as emerging risks and future risks.

3.3 Evaluation of existing methods for detection of precursors

3.3.1 Publications and literature

Identifying and utilizing precursors [31]

The document presents an extensive description of safety analysis principles in which precursors detection can be inserted. Detailed validity demonstrations of methods are done for the Top accidents categories and per risks domains, presents lines of defence / means of control and risks models. The methods presented are typically "Airline Operation" oriented.

Accident Precursor Analysis and Management [9]
Is the report of the 2003 National Academy of Engineering Program Office on the Accident Precursors Project to examine the complex issue of accident precursor analysis and management in aviation, the chemical industry, health care, nuclear power and security operations, identifies current practices and address some recommendations for future research. This seven-month project was designed to document and promote industrial and academic approaches to detecting, analyzing, and benefiting from accident precursors, as well as to understand public-sector and private-sector roles in using precursor information. The committee examined an array of approaches for benefiting from precursor information and discussed these approaches in a workshop held on July 17 and 18, 2003, in Washington, D.C.

Sensitivity of design Characteristics

Design Characteristics Sensitivity Analysis is used in engine engineering and possibly not well known by others communities. Sensitivity of each characteristic is initiated right at paper work by design office. It concerns any design, manufacturing or control characteristic whose variation or drift is evaluated in terms of functional consequences. It allows determining the so-called cliff effect. In a multiple variable sensitivity assessment, the analysis includes the combination of all characteristics permitting to detect the worst situation at a specified probability.

Possible benefits concern:

- Severity assessment of any deviation from initial design assumptions, design tolerances, operational, environment;
- Review of and manufacturing effort, permitting to strengthen some specifications having an impact on reliability/safety and to reveals excessive severity of others;
- Better defining qualification and certification regulations and compliance criteria;
- Waiver treatment;
- Incident analysis and precursors detection.

NASA precursor's analysis handbook [19]

The NASA Accident Precursor Analysis (APA) process [19] provides a means of analysing candidate accident precursors by evaluating anomaly occurrences for their system safety implications and identifying those that portend more serious consequences to come if effective corrective action is not taken. The purpose of the APA process is to identify and characterize potential sources of safety risk for which indications are received in the form of anomalous events which, although not necessarily presenting an immediate safety impact, may indicate that an unknown or insufficiently understood potential risk-significant condition exists in the system.

From reviewing studies on precursor detection, it becomes clear that:

- Very few, except those above, identified safety barriers/lines of defence weakening as precursors
- Some highlighted the key role of risk governance[2],[3].
- None identified interactions between domains as scenarios in which precursors have to be detected, or the links between development data that should be made available to precursors processing.
- None identified search for precursors based on changes or interactions between changes.

ASCOS should build on these approaches, e.g. as follows:

- FAST EME 1.1 methodology inputs permitting to search for precursors in area of emerging risks [7];
- Root cause analysis combined with Events Sequence Diagram permitting to spread out precursor alert at the level of the roots and detection at any sequences level;
- Organisation dispositions for a better harmonisation between industry and operators, creating a better link between precursor's data from development and in service precursor's analysis.

[2] Program or Project Management: refer to standards from ESA: (ECSS series / ECSS-M-ST-10C) or "Essential of project and systems engineering management" H Eisner - 2008

[3] Risk governance is a systemic approach to decision making processes associated to natural and technological risks, based on the principles of cooperation, participation, mitigation and sustainability, adopted to achieve more effective risk management, and that is convergent with other public and private policies.

3.3.2 The Future Aviation Safety Team (FAST)

The Future Aviation Safety Team looked at precursors, performed a survey of existing processes, introduced the AoC (Area of Changes) prognostic approach [8] and selected the basic methods that can be retained for further studies.

The FAST team concluded that most organisations are using already processes dealing to some extent with so-called precursors. Some practices are well formalised and efficient within a limited system or domain (e.g. aircraft engines) but are not well suited for analysis of interactions between different stakeholders. The key issue is that the way they are implemented does not bring confidence in precursor's detection capability. Implementation is an organisation issue. Failures of processes to detect precursors and to intervene successfully are mostly linked to:

- Difficulty in detecting events
- Criticality classification and corresponding allocation of priorities for investigation
- Analysis of consequences, trend analysis, interactions in particular accumulation of non-correlated but aggravating factors
- Inefficient, slow or biased decision making often linked to analysis outputs and to presentation of results.
- Detection of anomalies is an issue but not primary; procedural weaknesses are mostly related to communication, analysis and decision, the latter linked to insufficient safety culture at decision making level otherwise said, management related.
- Interface management is a real and growing issue. For example, relationships between engines and airframes' makers are endemically not good enough, ending up into incidents or accidents that would have been easily avoidable (e.g. all engines power loss).
- Increasing complexity of industrial organizations is also a growing problem.
- Both affect interfaces analysis, therefore certification and precursor's detection.

3.3.3 How can precursors be uncovered: examples of precursors detection

This section takes examples of accidents reports where precursors were either clearly identified after the accidents, directly mentioned in reports or through additional analysis of these reports. The purpose is to better understand why this detection was done after and not before the accident. Safety Boards reports are factual, based on past events, but contain information that allows to rebuild upwards the complete accident scenario with early sequences (development and certification), therefore detecting weakening or missing safety barriers. It's a way to use these reports beyond TSB objectives permitting to complete findings and recommendations.

Precursors belong to proactive and to prognostic safety. However taking lessons of past accidents to understand why precursors were not detected, is a deductive approach to improve existing processes and making them more proactive. That's what we do now.

Examples

1. Flight TK 1951 on approach to Amsterdam Schiphol (EHAM) RWY18R on 25 February 2009 highlights a situation where the main contributor of the accident was the failure of one of the 2 radio altimeters (RA). A failure improperly handled by both automation and pilots. Several radio altimeter incidents were recorded before and the sequence of events leading to the accident was available at manufacturer's level, possibly also presented to certification authorities and accepted as leading to a manageable situation therefore to an acceptable risk. The number of radio altimeters failures was in a way confirming that the situation was manageable. However it did not take into account that pilot's skills is decreasing. Note that decreasing pilot's skills is one area of change identified by FAST (see section 4). In this case decreasing pilot's skills would mean that the radio altimeter failure is not any more a minor event.

   Key words are: Events Sequence, AOC, Pilots skills and Risk reduction factor

2. Another example is JK 5022 MD 82 crashing on take-off from LEDM (Madrid Barajas) RWY 36L, 20 August 2008. The crew attempted to take-off with flaps retracted, adopting an excessive pitch attitude. The corresponding Angle Of Attack placed the aircraft behind the power curve. It stalled and crashed, killing 154 people. There were more than 2000m of runway available beyond the stalling position. An additional 700m ground run would be enough to gain 30Kts for a successful take off. The MD82 suffered from a triple failure:
   - Crew failure to properly set flaps in take-off configuration
   - Take Off Warning System (TOWS) failure to detect the invalid TO configuration and alert the crew accordingly
   - Crew failure to protect aircraft from stalling.

   The combination of the two first failures happened several times before (more than 20 recorded successful take off attempts with improper take-off configuration). Also there had been many cases of TOWS failures, more than 100 recorded. Obviously, these precursors were not taken care off. Among the reasons are:

   - The TOWS has never been designed to be a primary means for setting proper take-off configuration, simply a supplemental means.
   - It has never been intended to be a primary means for avoiding stalling crash on take-off, most pilots observing a maximum pitch angle and a smooth pitch input for avoiding stall.

   Therefore TOWS despite its low specified reliability was certificated with consideration of a "Pilot Risk Reduction Factor" such that the number of recorded incidents did not trigger any intervention. In this case, pilots are the key Safety Barrier. However new generation of pilots are losing "envelope protection skills" and the situation is changing. The number of pilots with military experience is quickly decreasing and other aircrafts models having envelope protection controls do not require these skills. The safety barrier was dramatically degraded over decades.

On a certification stand point, consideration of changes demonstrates that the TOWS specifications and the AMC (Acceptable Means of Compliance) are not valid anymore. This example also shows the potential benefit of considering failures not as isolated events but to consider how a failure can be part of a sequence of events that ends up into an accident. It should be continuously evaluated if the initial frequency and severity estimations in the original assessment are still valid. It shows also the relevance of performing a “Roots Cause” analysis that beyond the report allows drawing lessons at the depth of the roots and finding precursors of events at that level and generally at a wider scope.

Key words are: Root causes, deep treatment, AOC, events sequences.

3. ATC / ATM example. Separation assurance in Air Traffic Management is based on a process from central flow management to safety nets in flight. Each step contains identified safety barriers. They are identified at system’s designers’ level. These safety barriers behave like Reason’s layers that all together achieve the desired confidence level of separation assurance. Events already tracked and recorded (air-prox, level busts, TCAS R/A, safety nets activation) are regarded as precursors and analysed as incidents.

   Before accidents or incidents, we can detect other signals:

- The precursors are cases were IFPS proposals are not followed in flight. The event can be frequent. For example, an Initial flight plan is rejected by IFPS (Integrated initial Flight Plan Processing System) computers. Pre-flight discussion by phone between pilot and IFPS staffs concluded that the flight plan has to satisfy the computer but the flight will follow another route. It is a precursor of separation events apparently not recorded yet.
- Hand over between 2 adjacent control sectors.
    - At first radio contact, the controller shouts “FAF6432 immediately turn left 30°”.
    - Such urgent request reveals an improper coordination between control centres
    - Repetition of this event, several times with different flights, confirms recurrent coordination deficiencies between these sectors.
    - Proper coordination is a fundamental Safety barrier
    - Corresponding Safety Barrier degradation must be recorded, analysed as a precursor of separation issues, possibly severe.

Detection of these events as precursors requires involvement of designers and operators. A “Precursor Detection and Analysis Process” describing the sequence of events and associated safety barriers or lines of defence has to be established. Flow diagram, information to actors basically systems designers material has to be established communicated to operators with description of the entire logic.

The key words are: safety barriers, performance criteria, AOC, organization monitoring, operator’s safety culture.

3.4 Proposed process for identification of precursors

3.4.1 Lessons from examples

Accident and incident data

Accident reports usually describe what fails but not necessarily what caused the failure. They generally list previous similar failures considered as precursors. Engineering and safety analysis logic part of system's concept, allow completing upstream the sequence of events that generated the failure and find roots. This process is called "deep treatment". It identifies "Deep Roots Cause". Completing sequences of events as mentioned above, allows to find precursors located at the level of deep roots, well ahead of the failures.

Operational data and anecdotal reports

There may be operational events in all program phases, right from early development. Corresponding issues can be:

- Procedural weaknesses or failures.
- Short cuts in optimization / design trade-offs and / or FHA.
- Weak or lack of design justifications, success oriented options without back-up solutions.
- Qualification tests revealing insufficient margins.
- Under evaluation of difficulties to validate new technologies and / or to set up industrial organizations.
- Any infringement of safety management rules.
- In development, program reviews (reviews associated to every program milestone as specified in program management standards), if properly managed can be powerful safety barriers. Review reports can contain precursors and additional warnings concerning the engineering process (e.g. questions on the confidence level in design justifications of selected options. (e.g. validation steps short cuts).
- In operational phases, monitoring performances of Safety Barriers is part of the operational data mining permitting to detect precursors.

When one of the above mentioned events is detected, one should launch an additional survey for more accurate evaluation of consequences waiting for complete corrective action.

Extrapolation

This process includes analysis of on-going changes permitting to isolate where hazards could induce risks. A list of emerging risks is presented in chapter 4, permitting to launch specific search for precursors. For example, there are a number of precursors that point to reducing pilot skills, one of the major changes identified by FAST:

- Quick Access Recorders (QAR) analysis for detecting stall warning, stick shaker activations, non-stabilised approaches and any deviation from usual practices.

- A research study on behalf of the BEA using eye tracking noted a reduced attention paid to basic instruments (speed, altitude, attitude, sink rate, etcetera). This phenomena corresponds to a transfer of surveillance from human to machine, (pilots do not monitor aircraft physical status, his primary responsibility, but leave that to the computer). This is close to be a transfer of responsibility. This reduced surveillance may lead a pilot to miss a sequence of events and lose situation awareness. Then if pilot doesn’t understand what automation is doing, the situation may become critical.
- A study on highly automated aircrafts [32] tagged already the side effects of automation, not with the intention to call for less automation but to identify how keeping all of the good and none of the bad effects.
- Flight Examiners (FE) proficiency checks reports bring a similar result: the new generation pilots fly the computers not the aircraft. Older generation use the computers to fly the aeroplane and refer to the end result (basic instruments). In abnormal situations the pilot’s risk reduction factor is very different.

3.4.2 Generic process flow

In all cases precursors identification processes follow the same logic:

- IDENTIFICATION – monitoring the system performance continuously for precursors and comparing system behaviour against established standards or expectations to identify potential risks.
- EVALUATION - diagnosing the precursor factors contributing to or aggravating the potentially hazardous event, estimating the likelihood of future occurrences, and assessing the severity & operational significance of an anomalous situation. Evaluation would determine where to place precursors in an accidents sequence. The determination of root causes may orient (e.g. widen) search for other signals in program life cycle and organisation.
- FORMULATION – proposing changes in design, training, and/or procedures to mitigate recurrence of the event, assessing the system-wide safety risk of the intervention, estimating benefits and costs, and developing a strategy for implementing the identified change(s).
- IMPLEMENTATION – implementing on a small scale or in prototype, evaluating the performance of the intervention, refining, establishing performance standards, and monitoring to assess the efficacy of the intervention and to identify unwanted side effects.
- Once qualified according to the above logic, the complete implementation is a management issue. It requires procedures, tailored to existing organisation, handbooks intending to spread out associated safety culture, standards intended to be called up in safety management plans, audits intending to verify application.
- In a “Total System approach” implementation has simply to be done at the highest system’s level.

After this step providing a clear risk picture, the above process will be handed over to the risk management.

3.4.3 Recommended precursors assessment processes

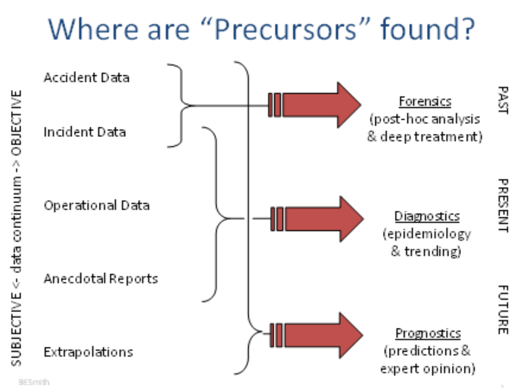

Figure 2 Where are precursors found? Courtesy of FAST [9]

Three main methods are selected:

Method 1: Data-driven methods

Data-driven approaches are based directly on process data and are model independent. These data-mining techniques compress and analyse large amounts of system data to detect unusual process excursions considered as abnormal situations, possibly precursors of accidents. For example, it can be discovered that events that were previously classified as minor can be contributors of severe occurrences if they are associated in sequences with other events. In that case their severity classification has to be upgraded and they can qualify as precursors. It becomes then necessary to retrieve all available data concerning these events, identify occurrences frequency, severity and revisit the safety analysis accordingly.

These methods can be completed with deep treatment. Deep treatment is defined as the identification of "root causes". An incident or accident or any technical event may have roots in engineering, certification, organization or so. The deepest roots correspond to the highest organisation level. Lessons can be drawn at all identified levels and generate precursors accordingly or at least define domains where to search for precursors.

For example, a degraded safety barrier increases the probability of failure and is a precursor justifying corrective action even if no incident has been recorded. Therefore description of the Safety Barriers, their function, performances criteria, is of major interest for precursor's detection but requires a management process (e.g. audit) permitting to detect such degradation.

As well, considering that process related issues are precursors, monitoring of safety systems and of the organisation in which safety is inserted is part of it. This requires also some audit associated with evaluation criteria.

For example introducing notions of "Continuity of service" allows evaluating the capability of a safety system to detect gaps wherever they are, the "integrity" would measure the level of confidence and its capability to detect where and how degradations or weaknesses reduce the capacity to mitigate risks.

Here we are in a data driven process, but incident data are completed by organization efficacy criteria.

Method 2: Model based approaches.

Unlike data-driven methods, model based approaches are analytical methods based on system models. These approaches measure actual system data and compare them with expected output based on a system model built from first principles. When a large process-model mismatch is detected, a fault (or precursor) is identified. For example, an engine turbine disk design is based on stress models completed with failure modes models. Over speed destruction of disks done in over speed test facilities have to demonstrate that a disk bursts out as predicted by the model. This is the starting point of the design and certification justifications. If later on, in operation or maintenance, some failures (e.g. cracks) show up or propagate differently than predicted by the model, this can be considered as a precursor of more severe occurrences. This approach, more frequently used during development, should become available to analyse any events during system's life, operations or maintenance. For example an airline flight has to be operated according to standards. SOPs (Standard Operating Procedures) define these standards. Any deviation from these procedures may mark a tendency towards degradation detectable with Method 1, but beyond that can tag a model discrepancy. For example more frequent activation of stick shaker or stall warning on take-off has to be considered as a precursor of take-off stalls and of a change of the "Pilots Model" that may differ from the initial assumptions. In particular, the Pilot's Risk Reduction Factor is of paramount importance in safety analysis, initial assumptions may not be valid any more.

Methods 3: Expert opinion

Expert opinion is extensively used in prospective methods. Experts provide their best guess of "What can be the future" and of "What could be the effect of changes". Well selected group members would be capable to evaluate tendencies or at least list possible evolutions that can be ranked then submitted to specific survey. For example the AoCs referring to the "pilots loss of basic airmanship" can trigger a "data mining" action "Method 1" or specific investigation such as QAR (Quick Access Recorder) survey with verification that the various operation models still represent reality, all of that conforming or not the experts' judgements. Application of the FAST AoC concept calls for expert evaluation of the effect of identified changes. Then according to establish severity ranking, it becomes possible to search for, precursors.

FAST provides indications where to searching for precursors (launch a survey confirming where precursors and measure are how severe and spread out is the hazard) permitting to react accordingly.

Combination of all 3 methods

Model based methods and expert opinions are more usable in early program phases before having data that come up only after having practical tests and operational results. Also any technical event showing up in operations or in maintenance is due to provide information feeding all methods. Examples mentioned in this study show already this interest of combining the 3 methods, in a fully iterative and complementary process.

3.4.4 Precursors in development phases

The initial engineering process

Precursors in design phases (concept, preliminary design, and detailed design) are of paramount importance for the whole life cycle. Many tests (validation, qualification and endurance tests) have been defined with the clear intention to identify limits and margins in extreme conditions, then detecting emergence (precursors) of degradations or out of tolerance behaviour and possible failure scenarios. Fine detection and analysis of precursors allows early corrective measures. This process applies to technical failures, process failures and to any extreme conditions, possibly resulting from combinations of technical characteristics. For example GNSS safety analysis combined the extreme satellite geometry conditions, propagation errors, SIS (Signal In Space) generated errors, receivers errors permitting to define the Navigation System Error (e.g. at 5σ or more) then to define and certificate Integrity Monitoring functions accordingly. The same logic applies to engines stalls, aircraft stalls, aircraft and fuel icing conditions, FADEC, etc.

Engineering support to operations

Above mentioned studies duly recorded during development and integrated in manufacturers technical background should be further processed during operational phase. If properly fed by field data, organization permitting, this engineering logic can contribute to confirm development assumptions, safety analysis results and to run the precursors detection methods mentioned above.

Creation and continuous monitoring of safety barriers is part of resulting corrective measures in development and later in operational phases with associated Continuous airworthiness.

Usually technical support to operations and corresponding feedback to manufacturers is very active in the first years in service, much less afterwards and rather poor for aging aircrafts. For example, verification of the validity of the initially designed MD 82 TOWS (Take-Off Warning System) for new generations of pilots may become difficult. In this case, contribution of FAST, identifying that the "pilots model" is changing and that investing in this domain has a considerable return on investment. Unfortunately it was measured after the accident.

Again, we are in a fully interactive process in which safety performances are performances of the whole, therefore of organization.

Interfaces management and increasing complexity of organizations already mentioned in the previous paragraphs show up again in risk reduction process during the entire life cycle.

We already noticed that improvement of safety processes has to address methods and on top of that gaps in their applications. Gaps reduction is part of management methods highly sensitive to interfaces management difficulties. On-going changes, in particular the increasing complexity of organizations creating many more interfaces is probably the most difficult challenge but the main source of improvement.

As well changes identified by FAST may create breaches in safety assessment requiring interventions at management level.

Again as already mentioned, introducing the notions of “Continuity of service” allows evaluating the capability of a safety system to detect gaps wherever they are, the “integrity” would measure the level of confidence and its capability to detect where and how degradations or weaknesses reduce the capacity to mitigate risks.

These criteria referring to the end results would be able to detect gaps between organizations rules and their applications.

3.4.5 Organisation issues

The previous development led to conclude that methods alone, even the best in the world are nothing if not driven by technical management, therefore integrated in program management.
Safety analysis is a transverse function that requires continuity and coherence:

- All along program phases
- Within all components of an industrial structure dedicated to a program (e.g. aircraft)
- Within the Total Aviation System (aircraft, ATC, airlines, authorities)

Safety is a performance that cannot be separated from the other performances, therefore safety management shall be completely embedded in program management and certification demonstrations by definition safety oriented, are made of design justifications accumulated all along program phases right from early concepts.
In the design phases, program management plays a key role in implementing precursors’ detection. A development phase should be driven to sort out a maximum of issues, to detecting most possible precursors.

Correcting corresponding failures either inside the system or at interfaces is fundamental for the future. The earlier failures are detected and analysed, the easier and cheaper are the corrective measures. Sometimes, high costs may block mitigation decisions. This is one of the reasons why problems, in particular those related to concepts, may never completely be sorted out. They continue to create difficulties in operations.[4]
We have seen that engineering data resulting from tests during the development phase can be an important source of precursors. Failure scenarios observed in development can be valid for “in service” phase. These data are an important part of industry know how, usually stored in industry internal data only and not published

Part of this information is inserted in certification files as design justifications, also restricted to certification folders and classified. Lessons learned are incorporated in internal standards permitting application to other programs and to keeping corresponding background alive, including knowledge of older systems still in operation. Keeping up skills and know-how is an organization challenge.

[4] 2% of LCC (Life Cycle Costs) invested in concept and preliminary design corresponds to 30% of LCC savings, a majority of costs result from incidents, accidents, grounding etc. (Average statistics from DOD programs presented by General Thomas Moorman, SOLE 93 Colorado Springs).

Therefore, Program management is driven by management methods, considered here as KEY methods for safety improvement. In particular the safety organization is due to create and maintain the necessary synergy between designers and operators all along a program.

Aging aircraft may suffer from lost know how and from reduced involvement of designers in product support. There again, precursors of new problems should be detected. Retrofits and new versions of aircraft may not be so well supported despite the risks of problems at interfaces between new and old systems.
Precursors' multifaceted role during a system's life cycle, underline how important they are, and how crucial it is to address Program Management in precursor detection.

Certification considerations

Within proposed new or upgraded standards the relation between certification and safety assessment methodology should be emphasised. In particular it should be suggested that

- An existing regulation that by nature cannot cover all cases, that also by nature results from past experience has anyway to be submitted to validity checks against engineering analysis addressing the real configuration to be certificated and updated accordingly. The updated design justification document has to be submitted to authorities as an upgrade to certification regulations. The certification reference remains at high levels rules such as the CS25/1309.
    - For example any parameter having an impact on fuel icing shall take care of everything in the aircrafts, in the engines, in the fuel characteristics, in the operations that, if combined in worst case: flight duration, altitude, atmosphere T°, engine settings, descent profile, Fuel Oil exchanger characteristics, sensitivity of all characteristics will not end up into fuel icing. The severity of this phenomena, leading to a failure mode common to all engines, the non-recoverable character of the situation (fast de-icing, irreversible degradation of fuel pumps by cavitations), requires to classify the event as highly improbable, justify to revisit existing (older) regulation and to verify performances of the organization in place (engine, aircraft, fuel specialists).
    - Stemming from the same logic, consideration of future state: new routes, higher altitude, longer duration, new procedures (continuous descent profiles of green approaches that may cool down more the engines). Sensitivity analysis covering identified changes should be part of the picture and possibly introduced into standards as cautionary practices, possibly as top level regulation.
- As well maturity demonstration of new technologies (e.g. composite structures) is requested by authorities for finalizing certification. However all steps from R&D to industrialization permitting to gain confidence and accept residual risks if any, are left to industry responsibility. Otherwise said the result is required not the process to make sure you'll get it. If the demonstration lacks robustness, problems will have to be sorted out by both industry and authorities.

The importance of the complete process motivated EUROCAE WG-63 and SAE S18 working groups to introduce recommendations going the same way in EUROCAE ED79A/ARP 4754 Revision A [16] in which program phasing and planning recommendations with associated review process have been introduced in Revision A.

New constraints

The above considerations highlight the importance of program management performances and of the integrated risk governance, directly linked to management standards and their application. As already said, the usual weak points are in early Program phases with a tendency to push difficulties forwards. Increasing complexity of industrial organizations with involvement of new partners creates additional coordination problems. Interface areas are typically where precursors should be detected and corrected early. New ATC/ATM systems and aircraft are becoming much more interfaced than ever. This new situation requires specific organizational dispositions permitting to work out all program management issues at the level of the whole on a continuous basis.

Authorities seem to have no intention to regulate programs management as done within Space and Governments/Military programs. Industries would like to keep freedom and consider their own practices as confidential. Therefore improvements have to come from "non-regulatory" actions, handbooks, and recommendations that progressively can be inserted into standards. At higher level, authorities should promote an operational coordination between Aircraft, ATC/ATM, airlines applicable to new situation resulting from SESAR and NextGen programs. Beyond that, the proposed effort through SAE S18 ARP standards should lead to an agreement between most actors on these principals permitting a "non-regulatory" but "consensus" basis. The bridge between aircrafts and ATC/ATM matters will need further clarification between partners.

3.4.6 Legal feasibility

Legal feasibility can be of major concern, as precursor detection can be understood as detection in advance of all types of accident. It is sure that accidents will occur in the future for which precursors will be identified during the investigation. Such precursors would be after analysis considered either as "not dangerous", or have led to corrective actions, which were not efficient, or too late. In such cases, the risk for judicial consequences might be considered by the concerned people or organisations as higher than if no precursor detection had been carried out. In addition, when an accident is avoided thanks to that kind of analysis, nobody will be aware of it. In other words, you can only point the negative performance of such a system. As described above, it should be highlighted that that kind of analysis is only a probabilistic evaluation of the occurrence of an accident, and that its efficiency or inefficiency cannot be evaluated by the fact that one or even several accidents occurred.

A specific legal survey must be performed. If not done, fear of legal claims may be a serious obstacle to safety improvement. Solutions are "anonymous reporting" or technical reviews intending to demonstrate that decision taken involved the best available "know-how", the best skills, the best possible technology and processes, and nobody would be able to do better.

3.5 Synthesis of results

Most organisations are using already processes dealing to some extent with so-called precursors. The key issue is that the way they are implemented does not ensure a reliable precursor's detection. Implementation is an organisation issue responsible for most failures of processes to detect precursors and to mitigate corresponding risks. Precursors can be found in accidents and incidents data, operational data, anecdotal reports and extrapolation of trends by domain experts. Lessons from past accidents and incidents also explain why precursors were not detected or not mitigated.

There are three main methods: data-driven methods, model based approaches, and expert opinion. In many cases a combination of them provides good results. In all 3 methods it is proposed to apply combination of deep treatment capable to identify root causes and precursors at the level of these roots; capable to detect events sequences, in which any event if placed with its role of potentially worsening a complete scenario; capable to detect procedures and safety barriers failures or loss of efficiency; can be right now, when implemented an operational precursor's detection process.

Improve precursors detection probability may be improved by:

- Making available development data identifying safety barriers, line of defense whose degradations are precursors. (The evaluation of the SB capacity to or not to, play its role, measures the remaining efficiency of the "safety barriers system" and compare it to initial assumptions)
- Identifying events sequences diagrams permitting to place any event in these diagrams. The same logic applies to procedures.
- Including corresponding surveillance in operations' analysis.
- Establishing links between the development logic, its ability to provide development validation results, (e.g. sensitivity analysis) usable for operational phases.
  - Achievable through developers / operators cross fertilization
  - Further develop root causes analysis in order to place incidents at the level of deeper roots and spread out precursor's research at that level. This process is also called "deep treatment" meaning corrective measures at deep roots level.
  - Complete accident reports analysis accordingly
- Precursors' detection and organisation dispositions should be part Integrated Logistics Support (ILS) dispositions as defined at program's level.

All the above aspect has to be integrated in technical support to operational phase in which the manufacturers continue to gather field experience and in return are able to use development data (e.g. safety analysis) to detect precursors. After detection, precursor's identification is a tree steps process: identification, evaluation and root causes analysis. Results from the above process, providing a clear Risk picture, will then be handed over to the Risk Management. Finally, Area of Changes and resulting emerging risks provide information on "where to search for precursor". It works like an advanced warning and control of safety issues.

4 Development of list of emerging risks

4.1 Introduction and study logic

An emerging risk is defined as a risk that is new, or a familiar risk that becomes apparent in new or unfamiliar conditions (IRGC [10]). A commonly used method for identifying and describing emerging risks involves creating a series of possible futures describing how the system of interest (the aviation system in our case) might develop. For each possible future sets of factors are identified that might jointly cause risk (IRGC [10]).
This way of working is also applied by the Future Aviation Safety Team (FAST), a group of multi-disciplinary, international safety experts whose primary focus is identification and publication of emerging and future risks across aviation and space sectors. FAST representatives were drawn from major air carriers, pilot communities, regulation and certification authorities, airframe and avionics manufacturers and research laboratories from Europe, the United States and Canada. The FAST philosophy promotes a holistic, system-wide view of safety in possible future aerospace environments. As FAST began its work in 1998, the team arrived at an early consensus position that to identify emerging risk possibly affecting the aviation system, one must first understand the context in which aviation operations occur. These contextual factors consist of both changes within the aviation system and changes external to the industry. To this end, FAST has identified and maintains a repository of Areas of Change (AoC). An AoC is defined as any phenomenon that will affect the safety of the aviation system either from within or from domains external to aviation, i.e. it is a possible description of (part of) the future. The time horizon for the AoCs varies between 5 and 25 years into the future. As far as we know, this list of AoCs is the only dedicated, comprehensive compilation of transformational phenomena affecting the global aviation system. The FAST AoC list is re-audited on a regular basis (approximately every two years) by the FAST Team. In addition, the FAST Team continuously monitors the aviation system and the external environment for new AoCs that may arise. For each AoC, the FAST team has identified hazards that may result from the change. Of primary interest are hazards generated by interaction among AoCs. A fundamental premise of the FAST approach is that the interactions and overlaps or gaps among the system to be assessed and the AoCs are the most likely catalysts for revealing and understanding future hazards. The AoCs can also affect the efficacy of risk control measures (safety barriers). Therefore the FAST recommends using the AoCs also to enrich the analysis of risk control measures by examining how the efficacy of risk control measures might be modified when interacting with the AoCs.

The most recent catalogue of approximately 100 Areas of Change [8] is a deliverable to the Aviation Systems Analysis Team (ASAT) within the NASA Aviation Safety Program. Among a wide spectrum of issues this catalogue in particular addresses:

- Characteristics of NextGen/SESAR
- Air/ground automation
- Shifts in aviation personnel demographics
- Pilot training deficiencies and simulator fidelity
- Runway incursions/excursions
- Flight deck and aircraft systems
- Unmanned Aerial Systems integration

- Proactive safety systems & SMS
- Commercial passenger/tourist spaceflight developments
- Hazards of de-orbiting satellite debris.

Potential hazards associated with each AoC are also listed. Approximately 450 near-, mid-, and far-term hazards are contained in this report [8].

For ASCOS, the FAST approach for identifying emerging risks from an analysis of Areas of Change as described above is considered appropriate. The AoC and associated hazards can also be used to help the search for precursors. Furthermore it is suggested that 'watch items' should be identified that confirm (or reject) that an AoC is taking place.

4.2 Lists of emerging risks

The list of emerging risks presented in Appendix A is taken from the FAST list of AoCs, dated 19 February 2013 [8]. The AoCs are in bold and are numbered. The numbers do not run continually due to the regular updating of the AoC list by the FAST group. Below each AoC is a list of hazards that are potentially associated with the change. These hazards are adapted from the hazards as identified by the FAST team. The adaptations were deemed necessary to remove inconsistencies. Appendix B contains a cross reference table that indicates how the AOCs are affecting the different domains of the aviation system.

4.3 Proposed process for continuous updating of emerging risks

The proposed process for continuous updating of emerging risks is based on the bringing together of a group of experts, similar to the approach that is followed within FAST.

While each expert involved in FAST is constantly on the look-out for possible emerging and future changes, it is the cross fertilization during the joint brainstorming sessions that make the FAST team so productive. It is important to note that some issues that showed up in recent accidents (AF447 (data, type airline, report N°), JK5022, TK1509) had indeed been identified by FAST before the accidents took place.

For more than a decade the FAST team has worked on a voluntary basis. Due to a lack of resources it is increasingly difficult to keep the team intact and to maintain the process of identification of emerging and future risks. For continuous updating of the list of emerging and future risks, a group like the FAST team is indispensable. The work is too important to depend on the voluntary work of some safety professionals. Therefore it is an option to establish FAST as a formal body with associated resources. Preferably, this should be done in coordination with international bodies such as ICAO, FAA, EASA, EUROCAE and/or SAE. The primary objective of the FAST team then should be to maintain the list of emerging and future risks and making it available to the aviation community.

4.4 Synthesis of results

The Future Aviation Safety Team (FAST) methodology, endorsed by EASA under EASp Action EME 1.1 [7], has identified and maintains a repository of Areas of Change (AoC). It should be noted that:

- FAST provides a Risk Picture of the future to **all actors** during the entire life cycle
- The present list of emerging risks presented comes out of FAST
- The AoC list provides indications where to searching for precursors (launch a survey confirming where are precursors and measure how severe and spread out is the hazard.
- The corresponding risk picture taken of in most engineering and safety activities concerns design justification of systems robustness to new risks therefore certification demonstrations.
- It is possible to enrich the analysis and efficacy of risk control measures taken by answering the question: “Will the safety enhancement resist to emerging risks?”

The FAST team works on a voluntary basis and it becomes more difficult to maintain this group due to lack of resources. The uniqueness of the results of the FAST group and the importance of the result as an input to a system wide safety assessment warrants the establishment of FAST as a formal body with associated resources rather than a voluntary group of dedicated safety professionals.

5 Conclusions and recommendations

5.1 Conclusions

The ASCOS methodology study:

- Has defined the conditions (needs and criteria) for implementation of a safety assessment methodology suitable to deal with the total aviation system and the entire life-cycle. This definition includes the means to address all the interfaces and interactions between the different domains and associated safety assessment processes, presented here as a total system approach. Part of these conditions is linked to methodologies, another part depend on application, tied up to management and most of its components.
- Performed a synthesis of existing know how on predictive risk identification and confirmed the added value of FAST/EME1.1 [7] considered as an augmentation process of existing methods.
- Developed an advanced process for the identification of precursors of (emerging) risks, in particular
  - o The search for precursors based on identification of area of changes and of emerging risks
  - o Deep treatment of incidents or accidents completed with Events Sequence Diagrams (ESD) identifying deep root causes and searching for precursors at the deepest level in identified events sequence.
  - o Detection of safety barrier and lines of defence degradation as precursor of severe scenarios
  - o Amplify the use of sensitivity analysis of technical characteristics in multiple factors interactions
- Developed a list of emerging risks, and proposed a procedure for continuously updating this list;
- Proposes introduction of additional program management recommendations into standards intending to ensure implementation of recommended methods,

Risk and safety management shall be a seamless process throughout programs' life cycle within and between all aviation domains. Rather than developing a new method from scratch, existing methods are evaluated in order to identify promising (combination of) methods that meet the above requirements and can be embedded in a certification scheme tied up to engineering safety analysis. This justifies selection of:

- Causal Model of Air Transport Safety (CATS) [14, 15], promoting the prevention of aircraft accidents through better understanding of aviation risks in terms of causes and magnitude.
- Future Aviation Safety Team (FAST) methodology (FAST/EME1.1 [7, 8], permitting to identify and take care of future and emerging risks.
- Program management dispositions, without which it may be difficult to follow a total system approach and systematically apply safety analysis, risks mitigations and proper decision making.

A. Existing know how

Existing safety methods identified represent the common denominator of methods applicable to the various aviation domains. All identified safety methods should be capable to incorporate inputs (e.g. emerging risks) from the FAST/EME1.1 process, to perform safety analysis of any system and systems of systems (total system), airborne or not, organisation and management permitting their implementation. For proper decision making, safety culture needs to be widely spread out at all hierarchy levels. FAST (Future Aviation Safety Team) has the unique capacity to bring more anticipation to safety and engineering as an augmentation process of existing practices without dramatic changes.

B. Precursors detection

Most organisations are already using processes dealing to some extent with so-called precursors but not implemented to ensure a reliable precursor's detection. Precursors detection and mitigation program concerns all life cycle phases, but with highest emphasis on early design phases. A generic process flow for identifying, evaluation, and handling of precursors is defined.

C. Emerging risks

The Future Aviation Safety Team (FAST) methodology, endorsed by EASA under the European Aviation Safety plan (EASp) action EME 1.1, has identified and maintains a repository of Areas of Change (AoC) [8] that:

- Provides all actors during the entire life cycle with a wide scope list of emerging risks;
- Allows providing design and certification justification of systems robustness to new risks;
- Is suited to enrich the analysis and efficacy of risk control measures and clarifies whether or not safety enhancements resist to emerging risks [7].

It is shown that about 10 years ago, the FAST identified emerging risks associated to major changes that would permit to predict events scenarios leading to recent accidents. Using the FAST methodology and its outputs (e.g. Areas of Change) as an input to a system wide safety assessment and using its capacity to bring more anticipation to most safety processes, is of paramount importance for the near and far future.

D. Safety assessment methodology

ASCOS WP3 is developing safety based design methods and tools that enable handling of current, future and emerging risks. The proposed combination of methods (CATS and FAST/EME1.1) address the Total Aviation System, and are expected to support derivation of Safety Objectives and Safety Requirements for any proposed change within the TAS (e.g. new technologies, operations, systems and/or products).

E. Certification

A safety assurance process totally integrated in all program disciplines is the core of the proposed improvement strategy. Updated design justification documents incorporating all safety analysis are considered here as bringing fundamental benefits in the certification process. In follow-up activities, further efforts should be dedicated to incorporation of the identified safety methods and supporting process flow for identifying, evaluation, and handling of precursors in the ASCOS Outline proposed certification approach [26].

5.2 Recommendations

Methodologies and fields of application

- Safety methods should be published as part of safety training material at any organisation level.
- Safety assessment results should be made available to all engineering and decision making levels.
- A total aviation system approach, as followed in the Causal model for Air Transport Safety (CATS), with its capacity to bring a better perception of all possible accident and accident avoidance scenarios is showing benefits and is recommended to be integrated within safety methods and processes.
- Safety methods should be an explicit part of the early phases of program management and promoted accordingly, so as to devote more safety effort in early program phases, in combination with engineering and certification, the latter considered as direct product from design justifications.

Precursors

- Identifying precursors and emerging risks is important in safety assessment processes. Precursors detection methods are recommended to become part of a standard or, at least, a handbook.
- Precursors' detection and organisation dispositions should be part Integrated Logistics Support (ILS) dispositions as defined at program's level.
- Improved detection of precursors can play a significant role in enhancing continuous safety monitoring activities.

Standardization

- Promote the creation and/or updates of standards towards a total aviation system safety approach.
- Encourage participation to the SAE S18 and/or EUROCAE Working Group 63, permitting to upgrade the EUROCAE and SAE ARP standards accordingly, with the methods and tools developed in ASCOS.

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Appendix A Areas of Change and associated hazards

1. Introduction of new aircraft aerodynamic and propulsion configurations

1. Technology advances outpacing the development of mitigations for unintended, emerging safety risks.
2. Flight and operational capabilities incompatible with current safety risk management methods.
3. Unfamiliar flight characteristics and control response.
4. Heterogeneous aircraft flying in common airspace.
5. Unpredictable wake vortex characteristics.
6. Evacuation delays.

3. Changes in design roles and responsibilities among manufacturing organizations

1. Inadequate transfer of expertise and/or inadequate interface management.
2. Lessons learned from past experience may not be sufficiently covered by FARs and CSs.
3. Dependence on single, specialty suppliers for a class of components by a number of manufacturers may create common-cause failures.
4. Potential loss of a larger systems view and understanding of the total aircraft design.

5. Introduction of new runway-independent aircraft concepts

1. Failure to yield aircraft rights of way.
2. Jet blast hazards in ground effect.

6. New supersonic and hypersonic transport aircraft

1. Exposure of passengers and flight crew to significant radiation levels due to high altitude flight.
2. Mixed traffic in terminal environment.
3. Unknown/unexpected loads and thermal stresses.

9. Accelerating scientific and technological advances enabling improved performance, decreased fuel burn, and reduced noise

11. Air traffic composed of a mix of aircraft and capabilities

1. ATC coordination problems when low-technology aircraft are mixed with high technology aircraft in high-technology airspace.
2. Loss of separation of mixed technology aircraft sharing same airspace.
3. NextGen/SESAR hazard condition: Several issues arise in a controller's sector, many involving mixed equipage. Controller reviews the events and prioritises response to them. Associated human performance hazard: Controller misprioritises response order of events.
4. NextGen/SESAR hazard condition: TMC Reroute is de-conflicted by automation probe. Sector controller resolves any remaining predicted problems with the reroutes as necessary. Associated human performance hazards: Sector controller overly reliant on automation and TMU to resolve sector issues. Controller fails to identify/resolve predicted problems in a timely manner.

13. Reliance on automation supporting a complex air transportation system

1. Flight crew spending excessive time in a monitoring role potentially compromising their ability to intervene when necessary.
2. Failure of the flight crew to remain aware of automation mode and aircraft energy state.
3. Unfamiliar modes of aircraft automation may result in a perfectly normal flying aircraft suddenly taking on characteristics that the pilot has seldom or never previously encountered.
4. Latent flaws in the displays or primary flight control system may go undetected, because not enough human-in-the-loop testing is performed.
5. Pilots may not be adequately trained to understand the philosophy of the automation design and of degraded automation functionality.

6. Inadequate software verification.
7. NextGen/SESAR hazard condition: Surface automation updates departure schedule based on time taxi clearance issued via data communications. Associated human performance hazard: Local Controller places aircraft in position to allow arrival aircraft to clear runway. Controller delays issue of takeoff clearance due to automation schedule disagreement.
8. NextGen/SESAR hazard condition: Local Controller issues takeoff clearance by voice when automation schedule advises controller of appropriate departure time. Associated human performance hazard: Controller issues a voice amendment, but does not enter amendment into ground surface automation.
9. NextGen/SESAR hazard condition: Weather or restricted airspace results in congestion that controllers must develop amendments for en route aircraft. Associated human performance hazards: Controller successfully develops route amendments, but fails to issue en route amendment to pilot. Controller issues voice amendment to en route aircraft that disagrees with route entered into automation.
10. NextGen/SESAR hazard condition: Ground controller coordinates runway crossing with local controller. Associated human performance hazard: Ground controller fails to coordinate runway crossing with local controller and authorises aircraft to cross runway (extremely high risk).

14. Advanced vehicle health management systems

1. Sensor failures producing single point failure of multiple devices.

18. New cockpit and cabin surveillance and recording systems

1. Diversion of scarce safety resources away from accident prevention to post-mortem forensics.
2. Crews “flying by the book” though that may not be the appropriate response in unexpected situations.

19. Emergence of high-energy propulsion, power, and control systems

1. Catastrophic failure of high-power gearboxes.
2. Penetration of pressurised fuselages by failed open-rotor fan blades.
3. Explosions due to undetected accumulation of combustible gases.
4. Burst hydraulic lines.
5. Failure of electro-mechanical actuators and signal/power transmission cables.
6. Failure of high-power alternators and power distribution systems.
7. Increased vulnerability to lightning strikes and sunspot effects.
8. Unexpected thermal runaway/overheating and combustion.
9. Deep discharge may short-circuit the cell, in which case recharging would be unsafe.

21. Advanced supplementary weather information systems

1. NextGen/SESAR hazard condition: Last minute flight plan changes are negotiated as necessary based on the weather changes. Associated human performance hazard: GA pilot fails to incorporate weather information into go/no-go decision.
2. NextGen/SESAR hazard condition: Post-departure, the pilot monitors weather updates as provided by automated Weather Advisories. Associated human performance hazard: GA pilot ignores recommended weather advisory.
3. NextGen/SESAR hazard condition: Post-departure, the pilot monitors weather updates as provided by automated Weather Advisories. Associated human performance hazard:
    a. GA pilot ignores recommended weather advisory.
    b. Commercial pilot ignores recommended weather advisory.

22. New cockpit warning and alert systems

1. Proliferation of caution/warning systems and alerts overwhelming the perceptual and cognitive abilities of the flight crew in critical phases of flight.

2. Changing crew workload.
3. Decreased flight crew situational awareness.
4. Failure to harmonise/optimise certification requirements for caution/warning systems including coordination and prioritization for multiple alert conditions.
5. Differences among automation use policies among different airlines may affect caution/warning implementations.
6. NextGen/SESAR hazard condition: Conformance Monitor generates excessive false / nuisance alerts. Associated human performance hazards:
    a. Flight crew ignores accurate conformance alert and fails to issue corrective instructions for a true alert.
    b. Flight crew becomes overly reliant on automation, fails to notice deviation when not alerted.
    c. Flight crew fails to confirm validity of conformance alert.

27. Next-generation in-flight entertainment and business systems
1. Hazardous effects of internal and external high-energy radiated fields emitted from these systems.
2. Inadequate certification processes for flight-critical aircraft systems and required maintenance procedures.

31. New glass-cockpit designs in general aviation aircraft
1. Failure of glass panel power supplies.
2. Inability to successfully revert to backup manual flight instruments.
3. Obsolete databases not containing new obstacles and departure/arrival routes.
4. Information overload.
5. Excessive heads down time.

33. Entry into service of Very Light Jets
1. Wake turbulence upset of lighter aircraft when co-mingled with heavier, faster jets
2. Increase in traffic.

36. Increasing implementation of Electronic Flight Bag (EFB) for efficient and safe operations
1. Obsolete databases not containing new obstacles and departure/arrival routes.
2. Cyber attack on database integrity.
3. Heads-down distraction of crew pre-occupied with EFB.
4. Low time between failure compared with certified equipment.
5. Poor visibility/contrast of display.
6. Failure of mechanical mount/electrical connection in cockpit.
7. Failure due to pressurization cycles.
8. Susceptibility to radiated fields in cockpit.
9. Failure of battery power.
10. Disconnect between aircraft/cockpit technology and airline infrastructure.

39. Increasing use of composite structural materials
1. Failure to detect sub-surface damage and de-lamination.
2. Shedding of micron-sised particles due to fatigue and chafing into cabin air with poorly understood health risks to lung tissue.
3. Damage due to lightning strikes

41. Ongoing electronic component miniaturization
1. Susceptibility of line replaceable units to ionizing radiation.
2. Fire hazard due to overheating.
3. Inadequate physical separation of miniaturised systems, increasing the risk of common cuase failure.

43. Highly-integrated, interdependent aircraft systems

1. High and low criticality functions sharing computing and data bus resources instead of being physically separated. Software-based isolation and independence is much more "fluid" and difficult to assure than relying on hardware.
2. Lost or erroneous inputs can result in a cascade of effects on the aircraft.
3. Inadequate self-checks to verify software for accuracy and integrity due to system complexity.

47. Changing human factors assumptions for implementing technology

1. Inaccurate assessment of total system safety due to failure to take credit for the human contribution to recover from adverse events.

51. Delegation of responsibility from the regulating authority to the manufacturing, operating or maintaining organization

1. Inconsistencies in compliance with certification and training regulations and the lack of FAA/EASA standardization.

53. Trend toward privatization of government ATC systems and airports

1. Pressures to reduce staff and equipment expenditures to minimum levels.

58. Shift toward performance-based solutions and regulations

1. The full safety implications of the introduction and interaction of these performance-based systems and regulations are not fully understood.

64. Remote Virtual Tower (RVT) operational concepts

1. Reduced sensory information upon which clearance decisions are based.
2. Inadequate awareness of other conditions on or around the airport that may affect flight operations (such as nearby weather formations).
3. NextGen/SESAR hazard condition: As departing aircraft taxi to runway, ground controller overly relies on observing automation to monitor conformance. Associated human performance hazard: Ground Controller fails to issue corrective instruction to resolve conflict because of lack of alert from surface automation. Ground controller is overly reliant on remote conformance alert.

66. Societal pressure to find individuals and organizations criminally liable for errors in design and operations

1. Reduction in normal incentives to perform research that may reveal possible design defects and operational errors.
2. Reluctance to file safety reports, thus reducing the possibility of learning from occurrences.
3. Industry members taking a more defensive rather than co-operative attitude towards regulators.
4. Disturbance of the open atmosphere in which industry and authorities jointly discuss safety issues.

67. Economic incentives to form partnerships and outsource organizational activities

1. Degradation of prior, robust, aviation cultures that were previously based on personal relationships.
2. Sudden ruptures in economic relationships including just-in-time supply chains, and available safety resources due to world market upheavals.
3. Failure to detect emerging issues resulting from faulty or broken reporting systems in dispersed organizations across world economic centers.

68. Global organizational models

1. Safety problems escaping notice due to lack of coordination.
2. Degradation of prior, robust, aviation cultures that were previously enabled by geographic proximity.

69. Evolution in lines of authority, command and responsibilities within the air transport system

1. Indirect or unclear lines of authority leading to confusion as to who is ultimately responsible for monitoring safety and implementing needed improvements
2. Hazards associated with bureaucratization:
    a. Delays in decision making;
    b. Poor communication among levels;
    c. Funding allocations;
    d. Opaque visibility of operational issues at higher levels of the organization.

73. Increasing complexities within future air transportation systems

1. Interactions among various stakeholders are not given adequate attention.
2. Gaps and overlaps in organizational responsibilities.
3. Stove-piped safety analyses.

78. Increasing sise of maintenance, ATM, and operations databases

1. Risk managers becoming overwhelmed by data.
2. Necessary data not reaching the appropriate parties.
3. Inaccurate maintenance data that is critical for calculations such as weight/balance and fuel loads.

The following important characteristics for shared databases may not be common among stakeholders

a. Parameter nomenclature, instrumentation accuracy, recorder resolutions and sampling rates
b. Filtering and processing of the data, while airborne and by the ground station
c. Data acquisition units across different aircraft fleet
d. Data sources for the same or similar parameters
e. Algorithms and techniques for deriving parameters
f. Event and incident definitions
g. Unit standards and conversion calculations
h. User operational environments
i. Safety and reporting cultures
j. Use and knowledge of statistical systems
k. Identification of which data should be shared.

80. Reduction in numbers of aviation personnel familiar with previous generation technology and practices

1. Knowledge of why aircraft are designed as such, how key maintenance is to be performed, and why the operational rules are as they are not being retained by individual or organizational memory.
2. Difficult to access legacy data storage systems
3. Inability of some operators to attract and retain senior people to mentor, guide and direct the less experienced and maintain safety systems.
4. Wholesale retirements within the current generation of aviation professionals.
5. Shortage of qualified inspectors and flight examiners.

82. Technologies and procedures enabling reduced separation

1. Uncertain availability of technologies and procedures enabling reduced separation especially space-based navigation/timing assets.
2. Uncoordinated ground flow control and departure/approach flows due to separation of functions.
3. NextGen/SESAR hazard condition: As departing aircraft taxi to runway, ground controller overly relies on observing automation to monitor conformance. Associated human performance hazard: Ground Controller fails to issue corrective instruction to resolve conflict because of lack of alert from surface automation. Ground controller is overly reliant on conformance alert. ASDE-X (based on transponder codes) is not currently used for ground separation purposes.
4. NextGen/SESAR hazard condition: Departing aircraft deviates from issued taxi route. Surface automation provides conformance alerts and is overly sensitive with a high rate of nuisance alerts.

Associated human performance hazard: Ground Controller ignores accurate conformance alert and fails to issue corrective instructions for a true alert.

5. NextGen/SESAR hazard condition: Arriving aircraft deviates from control instructions. Controller performs conformance monitoring with assistance from automation. Automation is overly sensitive with a high rate of nuisance alerts. Associated human performance hazard: Controller ignores accurate conformance alert and fails to issue corrective instructions for a true alert.
6. NextGen/SESAR hazard condition: Automation identifies candidates for delegated spacing. Associated human performance hazard: Automation indentifies incorrect candidate.
7. NextGen/SESAR hazard condition: Automation used to sequence aircraft. Associated human performance hazard: Controller fails to notice flaw in automation sequence.
8. NextGen/SESAR hazard condition: Pilots establish linkage with paired aircraft. Associated human performance hazard: Pilot fails to establish linkage. Pilot establishes linkage with incorrect aircraft.
9. Failure or lack of available backup systems.
10. Failure of systems in in-trail aircraft to detect and warn of high-strength wake vortices.
11. Inaccurate modeling of wake location and strength.

86. Evolution in the type and quantity of information used by ATM personnel

1. Errors due to lack of effective information integration and monitoring.
2. Unintended uses of new ATC information systems.
3. Failure to trust modern ATC information systems.
4. Failure of current facility displays to support information generated by systems such as ADS-B – incompatible developmental timelines.
5. Multiple operational modes available in ATC hardware leading to loss of awareness of the system status and mode confusion or distraction.

87. Changing design, operational, and maintenance expertise involving air navigation system (ANS) equipment

89. Increasing heterogeneity of hardware and software within the ANS system

1. Proliferation of new ANS technologies along side legacy systems may complicate maintenance, preclude software reuse, increase training requirements, and increase the potential for human error.
2. Lack of a unifying technical architecture.
3. Different or incompatible communication protocols/data formats, and user interfaces.
4. Support of many older systems is not being provided at the OEM level.

93. Increasing reliance on satellite-based systems for Communications, Navigations, and Surveillance (CNS) Air Traffic Management functions

1. Changes to existing procedures in certain non-normal conditions to maintain adequate safety margins
2. Exclusive reliance on single CNS technologies.
3. Intentional interference, jamming or spoofing.
4. Failure of CNS systems to communicate changes arising from dynamically reconfigured airspace.
5. Failure of satellite electronics, radio/satellite communication and ground infrastructure due to solar weather effects.
6. Failure of CNS satellite due to impact of (man-made) space debris.

95. Changing approaches to ATM warning and alert systems

1. Proliferation of caution and warning systems and alerts may overwhelm the controllers in periods of heavy workload.
2. Failure to prioritise alerts prior to implementation of such systems.
3. NextGen/SESAR hazard condition: Conformance Monitor generates excessive false / nuisance alerts. Associated human performance hazards:

a. Controller ignores accurate conformance alert and fails to issue corrective instructions for a true alert.
b. Controller becomes overly reliant on automation, fails to notice deviation when not alerted.
c. Controller fails to confirm validity of conformance alert.

96. Increasing interactions between highly-automated ground-based and aircraft-based systems

1. Potential incompatibilities between ground based and aircraft based systems that could affect safety.
2. Unclear delegation of separation responsibility to aircraft.
4. Lack of coordinated development of the safety case arising from uncoordinated implementation schedules between airborne systems and ground-based systems.
5. Lack of synchronization between aircraft and ground databases such as terrain and airspace boundaries and time signals.
6. Failure of procedures and hardware to synchronise flight plans in aircraft avionics and those in ground systems during turnaround at the gate.

97. Introduction of artificial intelligence in ATM systems

1. Potential for controller error if these systems are given limited control of ATM functions such as separation assurance independent of the human.
2. Actual or potential loss of separation where alerts and additional warning times are inadequate due to computational delay.

99. Increasing dependence on in-flight electronic databases

1. Reduced ability to cross-check information.
2. Failure of process to upload current databases during pre-flight.
3. Potential for entering incorrect data through the FMC/FMGS.
4. Cyber attack corrupts database or makes it inaccessible.

100. Increasing operations of military and civilian unmanned aerial systems in shared military, civilian, and special use airspace

1. Loss of separation between passenger aircraft and UAS
2. Inadequate coordination between military and civilian UAS in civilian airspace
3. Inadequate failsafe UAS designs and operations
4. UAS loses control link and is not visible to ground based automation/ANSP.
5. Control link failure between UAS and ground station; equipment failure; intentional takeover
6. System latency: Time delay in telemetry update or lag in aircraft response to PIC commands or guidance from observer.
7. Hazards associated with possible use of TCAS for separation assurance given that TCAS was developed as a last resort airborne collision avoidance system:

101. Redesigned or dynamically reconfigured airspace

1. Conventional hazard analysis impractical. For example, it is simply not possible to exhaustively enumerate all of the possible interactions that might take place in a dynamically reconfigured airspace of any considerable complexity.
2. Coordination issues with other facilities.
3. Controller awareness of constantly changing airspace boundaries.
4. Possible frequency issues at ATC facilities.

109. Increasing utilization of RNAV/RNP departures and approaches by smaller aircraft

1. Procedures are unfamiliar to pilots.
2. RNAV/RNP procedures may permit descent to ILS-like minimums into airports not having infrastructure such as runway approach and centerline lights.

3. NextGen/SESAR hazard condition: Pilot must navigate to RNAV/RNP route. Associated human performance hazard: Pilot deviates from departure route / navigates to wrong route.

113. Increased operations of lighter-than-air vehicles including dirigibles and airships

1. Inadequate sense-and-avoid capabilities during transit through altitudes occupied by commercial transport traffic for pilot-optional configurations.
2. Loss of control due to low-altitude wind shear.

114. Increasing operations of cargo aircraft

1. Increased traffic at less well equipped airfields
2. Operations at low traffic hours i.e. very late or at night (with associated noise issues)
3. Operations at higher and lower average take-off gross weights
4. Less concern for ride quality resulting in greater exposure to structural stress during turbulence.
5. Aircraft older than passenger-carrying aircraft (aircraft operate for a full "second" life after cargo conversion)
6. Load shifts.
7. Mismanagement of hazardous materials.

117. Very long-range operations, polar operations, and ETOPS flights.

1. Excessive crew duty times and inadequate crew rest
2. Passenger health issues (deep vein thrombosis)
3. Inadequacy of support and/or medical facilities at airports to which flights may be diverted and survival after a crash in cold environments
4. Inadequate fire suppression capability for duration of ETOPS
5. Different operational conditions (e.g. long duration at very low temperatures) may result in unanticipated system failures.

118. Emerging alternate operational models in addition to hub-and-spoke concepts

1. Inadequate infrastructure at smaller airports.
2. Hazardous new routes into these airports for noise abatement and other traffic concerns.

119. Increasing numbers of Light Sport Aircraft

1. Inadvertent flight into unapproved airspace.
2. Inadvertent flight into IFR conditions.
3. Malfunction or failure of consumer-level avionics utilised in such vehicles.
4. Loss of control of such aircraft due to inadequate pilot proficiency.

122. Accelerated transition of pilots from simple to complex aircraft

1. Failure of pilots to “stay ahead of the airplane” and anticipate effects of failures of basic systems supporting complex airframes
2. Failure to properly execute checklists associated with complex aircraft (post-takeoff checklist, for instance)
3. Failure to perform basic engine management during key phases of flight
4. Failure of a single crewmember to function appropriately in the event of incapacitation of a fellow crewmember.

125. Operation of low-cost airlines

1. Although this way of operating is not necessarily better or worse, the fact that it is different may result in unforeseen misunderstandings, (e.g., in safety oversight by the authorities), or when it comes to joint (low-cost and legacy airline) safety initiatives).

129. Growth in aviation system throughput
1. Adverse operational events due to complexity and unresolved international harmonization for regions experiencing the most rapid growth.
2. Shortcomings in execution of procedures due to changing of roles and responsibilities for pilot, controllers and others due to new concepts of operation.
3. Near misses, collisions, and runway incursions/excursions due to new systems such as traffic optimisers that will change operational paradigms and affect flight profiles and dispatch policies, procedures, and other aspects of aircraft operation.

133. Assessment of user fees within the aviation system to recover costs of operation
1. Reduction in flights and landings required to maintain proficiency
2. Reduction of utilization of fee-for-service capabilities such as VFR flight following and IFR services.
3. Less attention to “safety critical” functions based on user fees.
4. Lack of positive air traffic control for aircraft electing not to utilise fee-based services.

136. Increasing use of Commercial Off The Shelf (COTS) products in aviation
1. Unanticipated system failures.
2. Forced modifications
4. Counterfeit parts

138. Increased need to monitor incident and accident precursor trends
1. The increasing reliance on and acceptance of such systems will require comprehensive controls, procedures, and oversight to ensure that both data accuracy and integrity are maintained. This requires significant resources that cannot be spent in other safety initiatives.

139. Increasingly stringent noise and emissions constraints on aviation operations
1. Runway use policies creating potential for runway incursion/excursion and/or wrong runway take-offs/landing
2. New take-off and landing profiles which may reduce safety margins.
3. Noise curfews result in pressures to compress departures and arrivals into time slots near the beginning and end of curfew hours.
4. For Continuous Descent Approach (CDA) there are concerns with flying aircraft at reduced power at lower altitudes. The recovery rate for any kind of disturbance at lower altitudes is reduced significantly. At lower altitudes on less power, aircraft is more difficult to control due to air density. Bird strikes and engine stalls are much more likely at lower altitudes at reduced power and any last minute alterations could create result in loss of control.

141. Changes in aviation fuel composition
1. Engine failure/degradation due to:
   a. fuel specifications with differing properties such as lubricity, lower aromatic content, etc.
   b. cross contamination with incompatible fuels in pipelines.

144. Changing management and labor relationships in aviation
1. Loss of technical expertise in management ranks.
2. Realignment of relationships between management and labor resulting in role ambiguity and loss of technical oversight.
3. Poor resource allocation decision-making due to profitability concerns that are not cognizant of safety issues.
4. Exacerbated difficulty in staffing transitions and role redefinitions (including situational awareness training) resulting from investment, allocation decisions.
5. Labor-management disputes resulting in poor operational performance.

148. Increasing frequency of hostile acts against the aviation system

1. Cyber attacks on data links, databases, EFB's and iPads and digital/ electromechanical systems, jamming resulting in loss of RF signals used for critical CNS functions and FADEC operation.
2. Increasing sophistication and proliferation of explosive materials, biological/chemical toxic agents, and anti-aircraft weapons.
3. Increasing frequency of distraction, glare and temporary flash blindness from easily available and low cost of high-power lasers

161. Increasing numbers of (migratory) birds near airports

1. Greater likelihood of bird strikes

170. Increasing manufacturer sales price incentives due to expanding competitive environment

1. Delays in implementing a recommended mitigation (Service Bulletin)

174. New surface traffic flow management technologies

1. Database errors in surface traffic flow management technologies
2. Runway incursions/excursions due to lack of proper training, interface design, and usage
3. Equipage inconsistencies between aircraft and ground surface flow equipment

184. Increasing amount of information available to flight crew

1. Crew distraction resulting from information being presented on supplementary displays, requiring the crew to divide their attention
2. Flight crew confusion resulting from multiple modes being annunciated at one time
3. Poor retrofit integration with existing systems
4. Cluttering if information is presented on a single screen
5. Potential for information overload and excessive workload
6. Failure to display information in easily understood form, making monitoring difficult and complicating execution of emergency operating procedures
7. Failure to provide controls feedback and tactile cues to the pilot at critical stages of flight
8. Pilot does not see visual references at decision height but proceeds below minimums using enhanced/synthetic vision system.

185. Introduction of artificial intelligence (self learning) in aviation systems

1. Pilots not understanding intent and actions of AI avionics
2. Failure to achieve robustness, as defined under DO-178B guidelines - the very specific proof that under all application failure conditions, a single failure in one partition will not affect other partitions.

187. Shift in responsibility for separation assurance from ATC to flight crew

1. Intent and reasoning systems not well understood by the pilot
2. Unfamiliar, and unanticipated characteristics and interfaces
3. Lack of clarity when responsibility has been reassigned and how it may vary by phase of flight and type of airspace.
4. Breakdown in the fusion of current (radar) and near-term surveillance technologies (ADS-B In/Out) plus the procedures and phraseology that goes with them.
5. NextGen/SESAR hazard condition: Controller assists with weather avoidance, but overall responsibility remains with pilot. Associated human performance hazard: Sector controller fails to notice pilot request for assistance.
6. Computer-to-computer transfer of separation responsibility does not occur properly.

188. Introduction of new training methodologies for operation of advanced aircraft

1. Ineffective training methods resulting in lack of in-flight situational awareness, decision-making, and inadequate risk management.

2. Failure to identify risks beyond an emergent or abnormal procedure.

189. Shifting demographics from military to civilian trained pilots

1. Diminished basic airmanship including aircraft energy management and manual handling skills.
2. Lack of aircraft system knowledge and diagnostic skills by air crew
3. Inability to operate advanced aircraft in abnormal situations/attitudes, and recover from unanticipated situations when there is no checklist

200. Increased dependence on synthetic training in lieu of full-realism simulators

1. Part-task trainers and limited range of motion high-fidelity simulators may not sufficiently emulate loss-of-control situations to enable effective upset recovery training.
2. Negative transfer of training due to the lack of fidelity with the actual operational environment.
3. Airline crews learning tricks to fly the simulator and pass competency checks.

202. Shortened and compressed type rating training for self-sponsored pilot candidates

1. Emergency/abnormal scenarios are being combined together, even though the events are extremely unlikely to occur together based on the operational record.
2. Recent accident scenarios are emphasised and "routine" flight operations are being under-emphasised.
3. Shortened type rating may not provide opportunities to detect weaknesses in basic pilot skills among the candidates.

205. Operational tempo and economic considerations affecting flight crew alertness

1. Reduced flight crew alertness

218. Supplementary passenger protection and restraint systems

1. Devices could be susceptible to inadvertent activation, causing deployment in a potentially unsafe manner.
2. Rescue crews may inadvertently trigger gas generators used for air-bag-type protection systems.
3. Rocket-propelled recovery parachutes in some aircraft may be accidentally triggered by rescue crews

or may explode in post-crash fires.

220. Increasing functionality and use of personal electronic devices by passengers and flight crew

1. Degradation or failure of flight-critical firmware and hardware.
2. Interference with avionics or other systems in aircraft.

221. Introduction of sub-orbital commercial vehicles

1. Inadequate normal and emergency procedures for coordination with conventional vehicles.

222. Standards and certification requirements for sub-orbital vehicles

1. Failure to implement certification requirements in a timely manner due to pushback from industry.

223. Increasing frequency of commercial and government space vehicle traffic

1. Loss of separation between space and air traffic.

225. Entry into service of commercial, space-tourism passenger vehicles

1. Vehicle reliabilities not of the same order of magnitude as those of commercial aircraft.
2. Impact between deorbiting debris and commercial aircraft.

226. Changes in the qualifications of maintenance personnel

1. Acceptance of poor quality work either because of time limitations or because errors are not detected.

2. Reduction in the availability of certified maintenance personnel due to tightening of controls on maintenance procedures, limitation of working hours, vision tests, etc.
3. Reduction in the number of experienced maintenance inspectors.

230. Paradigm shift from paper based to electronic based maintenance records and databases

1. Degradation in maintenance quality of legacy aircraft which were previously paper-based but are transitioning to a computerised format
2. Inappropriate skill sets among maintenance personnel because of changing processes, tools, and techniques to support the new computerised systems
3. Poor task verification processes
4. Lack of coordination between maintenance and flight crews
5. Disconnect in processes for handling the formal aircraft log.
6. Failure of processes to fully inform crew of inadequate pre-flight aircraft status due to new electronic log entry formats; mismatches between manual, paper logs and electronic logs.
7. Loss of access to existing maintenance information during transition process to electronic records.
8. Cumbersome access to historic maintenance records required to be kept by aircraft owner.

236. Increasing use of virtual mockups for maintenance training and for evaluation of requirements

1. Maintenance errors arising from differences between the training environment and real line operations.
2. Failure to maintain configuration control between maintenance simulators and actual aircraft physical hardware.

241. Operational tempo and economic considerations affecting fatigue among maintenance personnel

1. Increased likelihood of fatigue among maintenance personnel.

242. Increasing single-engine taxi operations or taxi on only inboard engines of 4-engine aircraft

1. Excessive jet blast to achieve wheel un-stick.
2. Accidental single-engine take-off.
3. Creation of adverse thermal cycles in engine components.
4. Failure to develop standard operating procedures (SOP) and checklists to avoid cancelled take-offs and/or malfunctions.
5. Different failure behaviour (e.g. with respect to corrosion) of aircraft components on the side of the non-running engine/propeller due to absence of jet blast or propwash as a result of single-engine taxi.

243. Novel technologies to move aircraft from gate-to-runway and runway-to-gate

1. Runway incursions
2. Inadequate visibility from the flight deck
4. Failure to complete engine run-up and checklists
5. Damage to nose gear due to frequent coupling/uncoupling with propulsive tugs (for both towbar and no-towbar, wheel capture approaches).

244. High-density passenger cabin configurations

1. Lack of or poorly located cabin emergency equipment.
2. Reduced crashworthiness.
3. Presence of additional combustible or out-gassing materials in the cabin.
4. Passenger health issues.

245. Worldwide implementation of SMS

1. Failure to align the SMS policy with the working environment and conditions under which it has actually been developed resulting in ineffective SMS implementation.
2. SMS being used solely as a compliance exercise rather than as a genuine safety enhancement.

3. A potential risk in the implementation of SMS is an inconsistency between current SMS practices. In the future, the safety environment may drift away from the conditions under which the SMS was originally developed and approved.

246. World wide climate change trending towards warmer temperatures

1. Heat waves.
2. Increased precipitation duration and intensity.
3. More frequent and intensified winds and storms.
4. Rising sea levels and ocean acidity levels affecting operations of sea level airports.
5. Changed bird migration routes affect bird strike risk.

247. New aircraft recovery systems in general aviation and commercial aircraft

1. Flight closer to the edge of the flight envelope due to overconfidence in protections offered by full-aircraft recovery systems.
2. Flight into inappropriate meteorological or terrain conditions due to overconfidence in protections offered by full-aircraft recovery systems.
3. Rocket-propelled recovery parachutes in some aircraft may be accidentally triggered by rescue crews or may explode in post-crash fires.
4. Pilots incorrectly over-riding auto-pull-up systems; not unlike resisting stick shaker/pusher functions.

249. Increasing demands for limited radio frequency bandwidth

1. Unpredictable effects of closely-spaced frequencies utilised by different applications
2. Potential interference by digital packets serving different applications transmitted on same frequency.
3. UWB devices will likely generate enough interference to disrupt transmissions of other frequency users.

250. Shortage of rare-earth elements

1. Reduced availability of spare parts (electronics).

251. Introduction of new training methodologies for maintenance staff

1. Lack of ICAO guidance material on how competency based training can be applied to maintenance.

252. Smaller organizations and owners operating aging aircraft

1. Uncertainty about the quantity or type of maintenance and inspection required to ensure a high level of safety.
2. Structural failure due to fatigue cracking and corrosion.

254. Aging maintenance workforce

1. Shortage would suggest engineers are at risk of being overworked in order to maintain existing or increased tempo of maintenance operations.
2. Errors due to fatigue and related human factors issues.

255. New pilot licensing standards

1. Manual flying skills are being lost.

256. Decreasing availability of qualified maintenance staff at stations other than home base of operation

1. Lack of timely servicing of aircraft with potentially flight-critical component or system problems.
2. Poor quality aircraft servicing due to hiring of minimally-qualified staff.
3. Over-reliance on Minimum Equipment List (MEL) procedures as safety nets.
4. Incorrect information on the MEL within the airline operation center.
5. Inappropriate release of an aircraft by dispatch.

257. Reluctance among operators to implement voluntary proactive safety mitigations

1. Delays in implementing needed safety enhancements and/or mitigations indicated by in-service data trends due to fear of non-compliance with regulations and the resulting financial penalties.
2. Operators may ignore Service Bulletins from manufacturers unless backed by a requirement from the authority.

259. Shift in the demographics of newly-hired air traffic controllers compared with retiree skills and interests

1. Recruits may lack knowledge of aviation and flying found in retirees as a result of their aviation-related avocations (hobbies).
2. Process for selecting and placing new controllers does not sufficiently evaluate candidates' aptitudes because certain regulators do not effectively use screening test results or consider candidates' training performance to help determine facility placement.
3. Classroom lecture and testing process will make it easy to learn new material in order to pass the next test, and then forget the information learned - this is described as the "learn and dump" approach to training.

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

1. NextGen/SESAR hazard condition: Clearances are issued via data link where possible. Associated human performance hazards:
    a. Controller fails to issue clearance to pilot.
    b. Controller issues clearance to incorrect pilot
    c. Voice-issued amendment not entered into automation
2. NextGen/SESAR hazard condition: Controller sends clearance via DataComm. Associated human performance hazard: Controller fails to execute sending of clearance.
3. When approach and landing clearances are transmitted by data link to cockpit during this critical phase of flight, traffic watch ("heads-up") time may be reduced due to the fact that one pilot may be head down responding to and accepting DataComm clearance; especially below 10,000 ft. AGL.
4. Voice inflection, emphasis, and urgency will be absent in a text-based data communications system.
5. Loss of "party line" insight to clearance being provided to other aircraft. Spatial information on other aircraft locations provided on NAV displays does not replace intent information provided by listening to clearances provided to other aircraft.
6. Reliability and security of the CPDLC links may be compromised by cyber security vulnerabilities.

261. Operational tempo and economic considerations affecting air traffic controller alertness

1. Reduced air traffic controller alertness

262. Potential pilot shortages

1. Decreased pilot qualification requirements.

263. Shift from clearance-based to trajectory-based air traffic control

1. Synchronous garble and False Replies Unsynchronised In Time (FRUIT) preventing CPDLC messages from getting through.
2. ADS-B ground system failure; ground based automation does not receive ADS-B message
3. Inaccurate modeling of wake location and strength (drift, sink, persistence, severity)
4. Ground based conflict resolution not calculated.
5. Safety critical input data are incorrect, late or missing.
6. Software processes are too slow to reliably fulfill the automation requirements.
7. Breakout maneuvers, go-arounds, or missed approaches are not conflict free.
8. Controller misunderstands what the automation is doing with other aircraft in his/her sector.
9. Excessive controller workload due to TBO complexity.
10. Excessive controller workload due to TBO automation failure.

11. Pilot distractions: pilot makes mistakes when performing TBO navigation due to distractions from TBO related distractions (conformance alerts, etc.) in cockpit.
12. Pilot performs traffic avoidance maneuver to clear aircraft not accounted for in the current 4D trajectory.
13. Pilot performs weather avoidance maneuver not accounted for in the current 4D trajectory.
14. Pilot decision making when presented with weather information may not be uniform.
15. Aircraft emergency situations (off-nominal); aircraft has an emergency and must deviate from 4D trajectory.
16. Missed approach under TOB; unanticipated change to the 4D trajectory by the aircraft.
17. Received information from GPS incorrect or missing.

265. Socio-economic and political crises affecting aviation

1. Failure of States to carry out their safety oversight functions.
3. Overtaxing the capacity and safety infrastructure at airports and within the airspace structure.
4. Lack of both human and financial resources to execute safety oversight functions.
5. High costs of recruiting and retaining qualified technical personnel who satisfactorily meet the requirements of the positions including professionalism and integrity.
6. Failure to detect deficiencies due to inspector shortages.
7. Failure of a license/rating/certificate/approval holder to correct deficiencies identified by the civil aviation authority technical experts including faults, malfunctions, defects, and other occurrences that cause or might cause adverse effects on the continuing airworthiness of the aircraft.

266. Single-pilot cockpits for large commercial transports

1. Pilot incapacitation.

267. Increasing adoption of software defined radio systems in commercial aviation

1. SDR generate a lot of heat, and the availability of cooling on an aircraft is limited.
2. Highjacking or disabling of the avionics by unauthorised personnel.
3. Controlled information available on the SDR network could be leaked if the network was tapped into.

268. Decrease in turboprop fleets and operations

269. Proliferation of voluntarily-submitted safety information

270. Initiation of collaborative air traffic management

271. Improved surface operations technologies and procedures

272. Increased traffic flows involving closely-spaced parallel, converging, and intersecting runway operations

1. Wake turbulence.
2. Runway incursions.
3. Loss of separation.

273. Increased throughput utilizing improved vertical flight profiles and aids to low-visibility operations

1. Failure to recognise the need for and to execute a missed approach when appropriate.

274. Widespread deployment of System Wide Information Management (SWIM) on-demand NAS information services

1. Compromise of information:
    a. integrity;
    b. availability;
    c. confidentiality.
2. Database obsolescence.

Appendix B Cross reference between Areas of Change and aviation domains

Table 5 Cross reference between Areas of Change and aviation domains

AoC number	ATM/ANS	Aircraft & Airworthiness	Operations & FCL	Aerodrome
1		X		
3		X		
5		X		
6		X		
9		X		
11	X			
13	X		X	
14		X		
18			X	
19		X		
21	X			
22			X	
27		X		
31		X		
33	X	X		
36		X	X	
39		X		
41		X		
43		X		
47		X		
51		X		
53		X		X
58	X	X	X	X
64	X			
66	X	X	X	X
67	X	X	X	X
68	X	X	X	X
69	X	X	X	X
73	X	X	X	X
78	X	X	X	X
80		X	X	
82	X			
86	X			
87	X			
89	X			
93	X			
95	X			
96	X	X		
97	X			
99			X	
100	X		X	
101	X			
109	X		X	
113		X		
114		X	X	

117		X	X	
118				X
119	X	X		
122			X	
125			X	
129	X	X	X	X
133	X		X	
136		X		
138	X	X	X	X
139	X		X	X
141		X		
144	X	X	X	X
148	X	X	X	X
161				X
170		X		
174	X			X
184			X	
185		X		
187	X			
188			X	
189			X	
200			X	
202			X	
205			X	
218		X		
220		X		
221		X		
222		X		
223	X			
225		X		
226		X		
230	X	X	X	X
236		X		
241		X		
242		X		X
243				X
244		X		
245	X	X	X	X
246		X	X	X
247		X		
249	X		X	
250		X		
251		X		
252		X		
254		X		
255			X	
256		X		
257			X	
259	X			
260	X			

261	X			
262			X	
263	X			
265	X	X	X	X
266			X	
267		X		
268		X		
269	X	X	X	X
270	X			
271				X
272	X			
273	X			
274	X			