

# Resilience Engineering and Safety Management Systems in aviation

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**Abstract:** A Safety Management System (SMS) is an organized approach to managing safety. After the SMS introduction in other domains it is now introduced by ICAO and national authorities to support business and safety improvements. Another goal of the introduction of SMS is the facilitation of safety oversight by the national authorities. The publications about the SMS do not contain specifications of *how* methods should operate but merely list components that should be part of the SMS. Furthermore, claims regarding the effectiveness of a SMS are not yet substantiated by scientific research. Latest developments show ideas towards an integration of safety, quality and security. This integration may then further develop into Enterprise Risk Management (ERM) which may be linked to resilience engineering. This is the first paper of a series regarding my ongoing graduate research project which will attempt to define the functional structure of a SMS and the essential methods, models and classification schemes. These will be based on safety science and resilience scientific literature and taking into account the requirements as described by authorities such as ICAO, FAA and IATA.

## 1 INTRODUCTION

This paper is a report from my ongoing project to propose a functional SMS for airlines. Recent developments in aviation safety are focused on combining different safety functions into a Safety Management System. The International Civil Aviation Organization (ICAO) published, recommended guidelines for national civil aviation authorities. In the recent ICAO safety management manual (DOC 9859 First edition 2006) the concept of a SMS is described.

At the same time organizations such as the FAA, Transport Canada (TC), International Airlines Transport Association (IATA), the Flight Safety Foundation (FSF) and others promote the application of SMS principles by aviation service providers such as airline companies.

Two arguments drive the promotion of SMS by the regulatory authorities. Air travel is expected to grow over the coming decades. A Boeing study estimates an increase in the number of aircrafts from 17500 in 2005 to about 36000 in 2025. Without safety improvement the industry is expected to suffer one major hull loss per week in the years to come. This is not good for the airline image. Furthermore due to the growth of aviation activities, budget constraints in the safety oversight function of the authorities require a new way of safety oversight that reduces costs.

The authorities claim that safety will increase and costs will be reduced by use of SMS's. Cost reduction can be found not only in less damage but also by less irregularity costs. This claim is confirmed already by an airline that has introduced a SMS, but research to substantiate this is not yet published yet.

## 2 THE NEED FOR MODELS, CLASSIFICATIONS AND METHODS

All main documents published by the organisations mentioned above have so far focussed on *what* not on *how*. TC stresses in a SMS guide on the importance of systematically linked components rather than individual components that make up the SMS. Compatibility between the subsystems requires a common theory. Models and concepts should be compatible to enable transfer insights from one method to another. An example could be the improvement of the risk analysis (feed-forward or pro-active) based on lessons from re-active accident investigation. Compatibility between the SMS subsystems may seem obvious, current practices show isolated methods and or lack of compatibility between them. Compatibility by design is one of the objectives of this project.

To allow well based trade-off and other resilience decisions safety management needs to be up to par. As Weick (2001) states “Effective resilience requires quick accurate feedback so that initial effects of attempted improvisations can be detected quickly and the action altered or abandoned if the effect is making things worse. Systems with slow feedback essentially give up any chance for resilience.” By the provision of quick feedback and the ability for new interpretations of collected data by audits and investigations this SMS proposal will attempt to be part of resilience engineering methods.

My proposed SMS should be able to grow into or align with ERM. In ERM all types of risk are evaluated from operational to strategic level and may concern even the restructuring and survival of the organization. Since this is also the field of resilience engineering the continuum from safety to resilience has to be covered by theory and methods.

Methods, classifications and models are essential aspects of an effective SMS (Hollnagel 1998). The method describes the steps to take for e.g. accident or risk analysis. The classification scheme provides a consistent description of factors. The model serves as abstraction of the phenomena being studied. My ongoing research project will describe the models, classification and methods, as evaluated so far, for a SMS in aviation.

## 3 PARADIGM

Many perspectives on problems are possible and the answers are relative to a paradigm. To support the discussions it may help to be explicit about the philosophical view that underlies the theories and models used in this work. Philosopher Kuhn (1962) defines a scientific paradigm as: *what* is to be observed, the kind of *questions* that are supposed to be asked, *how* these questions are to be structured, *how* the results of scientific investigations should be interpreted.

The paradigm of systems theory is underlying the models proposed in this work. Systems theory studies the relationships between interacting wholes. Each whole can be a subsystem of a larger whole. The unit of analysis and the description of the systems and its boundaries is subject to the purpose of the analysis. Models and theories used in this work originate from the field of control theory, Cognitive Systems Engineering (CSE Hollnagel, Woods 1982), and the ‘new view’ of human factors.

As a consequence of applying the theories and models in this paradigm, system (human) performance is seen as interactions of complex systems in a dynamic environment satisfying, under resource constraints, multiple, often conflicting, goals. Some often used concepts are not valid in this paradigm such as: “human error”, decomposition, root causes.

Next three sections will describe the concepts of system, management and safety. In the light of a SMS with the interpretation of this project.

## **4 SYSTEM**

The system in the concept of SMS means a framework of functions to manage safety. The IATA defines system as: ‘A combination of interacting or interrelated elements within an organisation functioning in a coordinated manner to achieve desired outcomes.’ (IATA IOSA manual). In this case the goal is to manage system performance to prevent loss of control.

Ultimo, in the language of CSE the SMS can be viewed as a joint cognitive system (JCS) controlling safety. The CSE definition of a cognitive system is: ‘A system that can modify its behaviour on the basis of past experience so as to achieve specific anti-entropic ends.’ This perspective allows the use of control theoretical concepts.

In system design the perspectives of structure, function, process and context are required to make the whole understandable Gharajedaghi (2006). This holistic approach was preceded by the focus on structure, thereafter focus shifted to objective and functions. Then followed the total quality movement with its focus on control and process. All three perspectives along with environment are interdependent and mutually exclusive and collectively exhaustive. Model, method and classification are thus related. In the design of a SMS these notions should be taken into account.

## **5 MANAGEMENT**

In the attempt to manage safety, the definition of safety will give hints for the goals and means of management. Management is about controlling the function of the system towards the safety objectives. The process of management requires actionable data, resources, goals and means.

ICAO emphasises that safety is a managerial process, shared by the state (government regulators) and the aviation operators or service providers. This indicates safety management is not about the individual human operator but about the organisation controlling safety by controlling performance and risk.

To extend the scope from regulatory safety management objectives to the resilience engineering perspective on requirements for safety organisations Woods (2004) summarises requirements to make safety management successful. The 4 ‘I’s for a safety organisation are:

Independent; conventional assumption in senior management should be challenged

Involved; support organisational decision making

Informed; gather information and show how the organisation is performing

Informative; use information about organisational weaknesses and propose interventions

The effect of these aspects should be evaluated to see what consequences this has for the structure, functions and processes of the SMS.

## **6 SAFETY**

The operationalisation of safety should provide directions to measure and control safety. Based on the requirement of being manageable ICAO, FAA and other regulatory organisations translate safety into acceptable risk. It is argued that the factors that are likely to create accidents as well as the severity of the outcomes can be identified and analyzed. Therefore effective safety management is essentially risk management. (FAA 2006)

The effect of the ICAO and FAA safety definition is that much focus is put on risk management. Then a quality management approach should be applied to the control of risk and this is what the FAA introduces as 'safety assurance'.

A more general definition of safety as mentioned by Hollnagel (2004) is the absence of an undesired outcome. This definition allows a wider perspective on possible issues affecting safety but needs further specification for safety management. This more general definition also supports a common perspective on safety in different parts of the organisation e.g. aircraft maintenance and the occupational safety and health office.

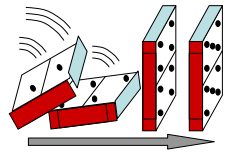
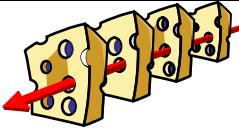
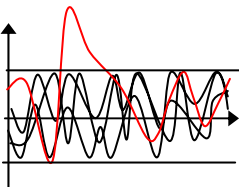
Safety according to Weick (2001) is a dynamic non event. It is not a property of static parts but the outcome of complex processes. Accidents occur when external disturbances and dysfunctional interactions between system components create a situation that gets out of control. With this perspective safety can be viewed as a control problem (Leveson 2004), (Rasmussen 1997). The function of safety management is then to control system and sub-system process performance.

Safety as control problem supports a control theory approach to manage safety and this definition of safety will be used in my model and method development.

### **6.1 Accident model**

Einstein stated 'the method defines what you see'. the use of models is not without consequences. The description of how functions or tasks fail requires a model. The model determines what information need to be collected to provide an explanation of the failure. The anatomy of an accident can be modelled in a accident model. Hollnagel recognises three generations of accident models.

Table 1: Three approaches to accident management

Accident model	Metaphor	Management principle	Nature of causes	Response type
Sequential Accident development deterministic (cause-effect links) "Domino"		"Error" management	Causes can be clearly identified (root cause assumption)	Eliminating or containing causes will exclude accidents
Epidemiological. Accidents have both manifest and latent causes. "Swiss cheese"		Performance deviation management	Blunt end / sharp end deviations have clear signatures	Deviations leading to accidents must be suppressed
Systemic Variability can be helpful as well as disruptive. "Functional resonance"		Performance variability management	Sources of variability can be identified and monitored	Some variability should be amplified, some reduced

Aviation is a dynamic, complex and ultra safe domain (Amalberti 2001). Simple accidents are hard to find (if they even exist at all). Therefore the accident model must be able to take into account the complexity of the domain. A commonly agreed suitable description of the current complexity of accidents in modern socio-technological domains like aviation is that accidents (and incidents) occur due to unexpected dysfunctional interactions between system components (human and machine) often related to external disturbances. Leveson (2004) and Hollnagel (2004) argue for systemic models that capture this complexity. The challenge is to have a 'simple' model representation to explain the accident to management. Part of the success of the 'Swiss cheese' metaphor is the power of the graphical representation. The functional resonance model as depicted in the table above is a member of the systemic accident models that also has a high graphical representation power.

The ICAO, FAA and IATA SMS publications do not provide specific accident models, but often representatives of the mentioned organisations use the "Swiss cheese" metaphor indicating the use of an epidemiological accident model.

Scientific publications about SMS such as IRISK(Bellamy 1999), SAMRAIL (Hale et al 1997), WORM (Hale et al 2001) and CATS (Ale et al 2006) use the bowtie accident model which can be classified in the family of epidemiological accident models.

This project will use the systemic accident model FRAM to model performance.

## 6.2 Functional Resonance Accident Model

Compatible with CSE concepts, Hollnagel has developed the Functional Resonance Accident Model (FRAM, Hollnagel 2004). This model describes how functions of (sub)systems may under unfavourable conditions resonance and create situations that are running out of control hence are unwanted. The consequence of using this model is the search for functions (processes) variations and conditions that influence each other and than may resonate in the case of risk analysis, or have resonated in the case of accident analysis.

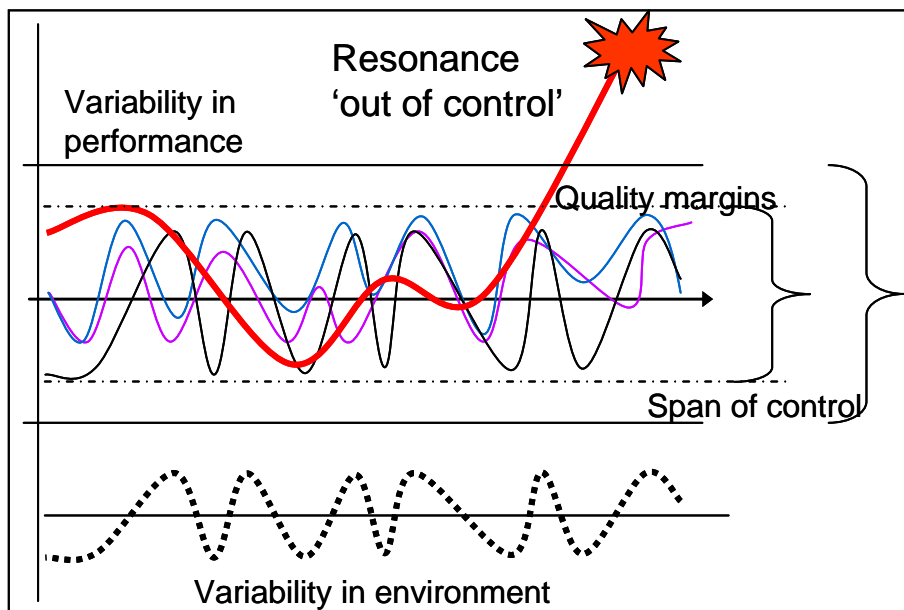


Figure 1 Functional Resonance Accident Model (Hollnagel 2004)

Performance variability is normal in the sense that performance is never stable in an open system as aviation. Internal variability, due to adaptations required by resources constraints, and external variability due to changes in the environment are normal. System variability is also desired since it allows learning from high and low performance events (Hollnagel 2004).

The use of FRAM as accident model requires performance indicators to permit Performance Variability Management (PVM). Management of performance variability requires observable, valid and sensitive indicators that reliably show that loss of control is approaching and furthermore control must be available to counteract or stop the process.

## 6.3 Performance indicators

Since the performance itself can not be observed, indicators, analogue to a thermometer for a medical doctor, must be developed. The quality of the indicators plays a crucial role for the effectiveness of the SMS. Indicators should not be picked just because they are easy available, they should be evaluated on some critical requirements. The

methodological perspective requires indicators to be: external valid, construct valid, sensitive and reliable. Hollnagel (2006) proposes that performance indicators are, objective and available, quantitative or simple quantifiable, meaningful and compatible with existing programs.

It is important to realise that this is a systems approach and that is the unit of analysis is performance of systems So the focus is not on individual parts, the human and machine, but on the performance of the joint cognitive systems.

## 7 SMS MODELS, CLASSIFICATIONS AND METHODS

Model requirements (based on Hale 1997) and how they are met:

It should model the dynamical nature of safety management.

Safety is seen as control problem and the result of the dynamics in complex systems.

It should link accident and incident explanations via risk control functions (barrier performance) with regular management functions.

Accidents are explained by performance variability. Part of the variability is the performance of the barriers. Barrier's performance and working conditions are controlled by management functions.

It must provide a common language to describe and model all aspects of the system

The paradigm discussed above creates commonality in the models, classification and methods of the SMS.

Requirements based on project objectives and how they are met:

It must be compatible with new developments (Yantiss 2006) and principles in safety, quality and security management.

Unwanted situations are prevented by maintaining control over processes, this is a generic concept.

It should at least be compliant with the ICAO, EASA, FAA, TC and IATA regulations.

In aviation compliance with these organisations regulations is seen as mandatory by the airlines.

It should be compatible with and supportive to resilience engineering methods, at least with our current understanding of resilience.

Safety and resilience are related and methods for both concepts should be compatible.

Using the same paradigm for the SMS as for resilience engineering gives best chances on a future proof SMS.

The SMS at a high conceptual level will be like a basic control loop.

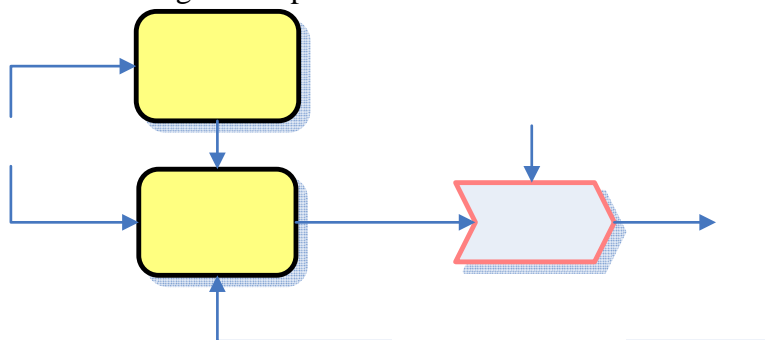


Figure 2 Safety as control problem

**7.1 Performance Variability Management control model**

Management of safety is like controlling a process. The proposed SMS can be seen as a JCS. A more specific perspective on control gives the concept of the Extended Control Model (ECOM) (Hollnagel 2001). In this model different levels of control that occur simultaneously are described. It is comparable to the business process modelling concepts of: strategic, tactical and operational activities. Each higher level has different activities and influences the level below by constraints, resources and input. This is an agreement with many business management theories.

Table 2 ECOM levels of control for controlling a car

	Tracking	Regulating	Monitoring	Targeting
Type of control involved	Compensatory (feedback)	Anticipatory (feedforward) + feedback	Condition monitoring (feedback)	Goal setting (feedforward)
Demands to attention	None (pre-attentive)	High (unfamiliar actions); Low (familiar actions)	Low, intermittent	High, concentrated
Frequency of occurrence	Continuous	Medium to high (context dependent)	Intermittent, but regular	Low (preparations, re-targeting)
Typical duration	<1 second ("instantaneous")	1 second - 1 minute ("short term")	10 minutes - duration of activity ("long term")	Short (minutes)

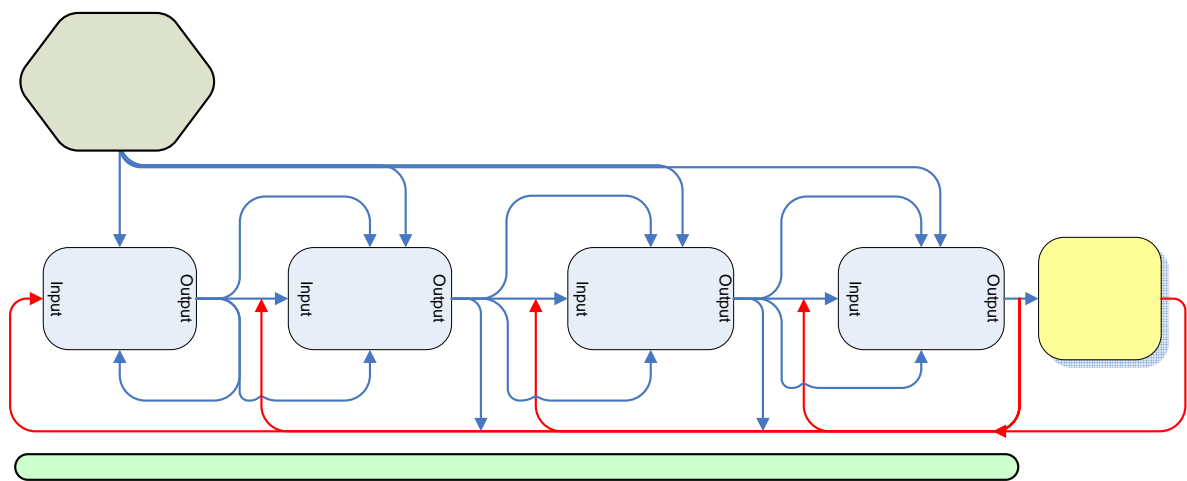


Figure 3 Performance Variability control loop based on ECOM



### 7.2 Viable System Model (VSM)

Based on cybernetics management theory Beer (1985) has proposed the VSM as a model of an organizational structure of communication that should be able to adapt and survive in a changing environment. This supposed ability has remarkable overlaps with aspects of resilience as proposed by Hollnagel Woods and Leveson (2006).

The organisation can be viewed as constituting of two parts: the Operation which does are the core business (production), and the Meta-system which supports the operations, does the planning, accounting etc. Figure 4 depicts these two parts and the environment with the interaction channels. The basic VSM is more detailed in figure 5, showing 5 system functions and the relationships.

Beer has characterized 5 VSM system functions that are critical for viability and these functions are invariant in viable system. Beer suggests that lack, or degradation of any function will lead to problems in the organisation, like stress, and the organisations viability is in danger.

Table 3 VSM system functions

System 1	Operation	The entire collection of interacting Operational units
System 2	Meta-system	The system responsible for stability/resolving conflict between Operational units
System 3	Meta-system	The systems responsible for optimisation/generating synergy between Operational units
System 4	Meta-system	Future plans and strategies. Adaptation to a changing environment.
System 5	Meta-system	Policy

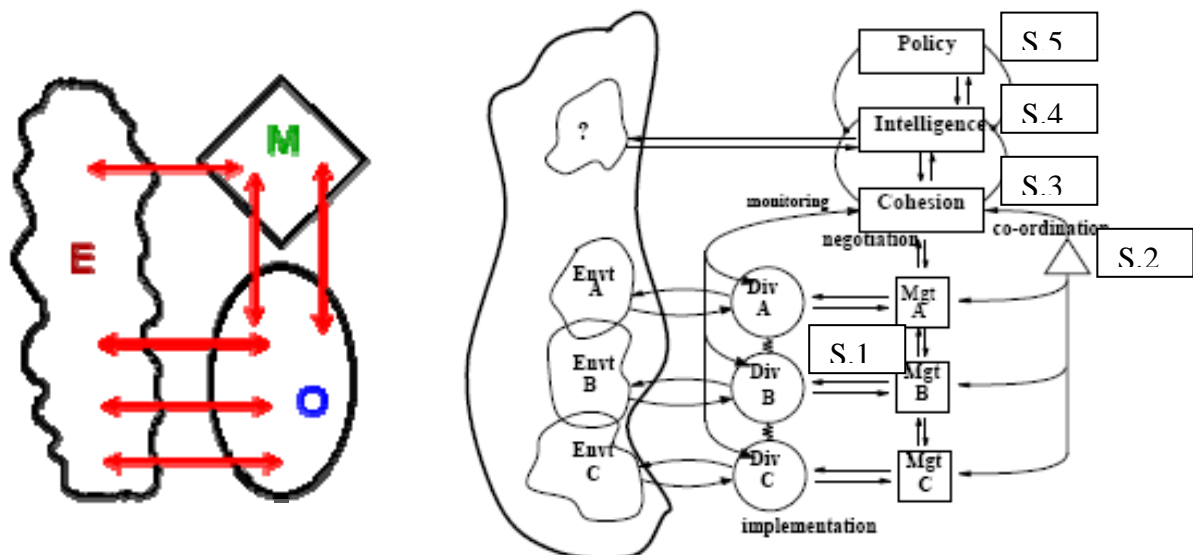


Figure 4 Environment, Operation, Meta-system Figure 5 Viable System Model

### **7.3 Evaluation of ECOM and VSM**

Both the models of ECOM and VSM will be evaluated against the ICAO and IATA SMS requirements. Other criteria to establish the most useful approach for SMS structure description are under consideration.

### **7.4 Management of Safety Pre-Conditions**

It is commonly agreed that working conditions shape performance (Reason 1997) therefore if the organisation is capable and willing to control working conditions performance can be improved. Adjustment of working conditions is re-active when it is initiated by feedback from processes. Control of working conditions is pro-active if it is initiated by discoveries that the context of the organisation itself is changing. This will have effect on the working conditions inside the organisation.

The FAA publication on SMS does not include actions aimed at pro-active organisational context monitoring and a method for adaptation. Also the ICAO Safety Management Manual is not explicit on monitoring the organisation's context and anticipating changes that might eventually result in increased risk. The risk may increase when the organisation's model of risk is not updated.

Tripod (Groeneweg 2002), a risk management concept, has a classification of Basic Risk Factors (BRF) that should be under control of the organisation to prevent human failure.

In I-RISK, ARAMIS (Guldenmund et al 2005), WORM (Hale et al 2003) and CATS (Ale et al 2006) the concept of delivery systems is used to express management's responsibility for managing (provide, use, maintain and monitor) risk control measures. This can be seen as indirect managing of the working conditions.

Resilience engineering concepts focus on adaptation to a changing organisational context. (Hollnagel, Woods, Leveson, 2004). A SMS must be supportive to three qualities of resilience, anticipation, attention and response, to keep the systems adaptation to changes in the environment under control. The SMS should be compatible with these developments. A SMS build in the same paradigm as resilience engineering might stand the best change to be adaptable to these developments.

In an initial comparison between the Tripod's BRF's, the CATS delivery systems and FRAM Common Performance Conditions (CPC) (Hollnagel 1998) the latter seems to be the most complete and suitable for linking management processes with working conditions. Completeness of the CPC must be evaluated and the resulting set of descriptors will be nominated as Safety Pre-Conditions (SPC). The SPC need further research but an example is that the CPC of "training and experience" is linked to the management processes of training and selections of pilots and other employees.

The FAA has conducted an Air Carrier Operations Systems (ACOSM 2001) study to develop a system engineering model of the generic functions of air carrier operations. ACOSM concentrates on the following key air carrier operation processes: Operational Management, Air Transportation, Aircraft Maintenance, Personnel Training, and Operational Resources Provision. ACOSM can be linked to SPC's to model how the management processes can influence Safety Pre-Conditions.

Management of the SPC's can be approached similar to performance control in the sense that control takes place on different levels. Further research must indicate whether ECOM can be used as in PVM or whether the other levels are more appropriate.

Previous sections showed that ECOM can be used to model the control processes and that the CPC's, with possible adaptation, will be used as classification for context in accident and risk analysis. SPC is a classification in development and will be used to describe the working conditions under the control of management. The models and classifications should be evaluated for compatibility with ERM.

## 8 ENTERPRISE RISK MANAGEMENT

Enterprise Risk Management is much broader than losses, insurance and claims. ERM is targeted at managing any factor that represents a threat to a company achieving its strategic objectives. The ultimate desired outcome is to reduce the variability in the organisation's process execution and thus produce more predictable financial and operational results.

The objectives of an organisation can be described by four categories (COSO 2004)

- Strategic, high-level goals, aligned with and supporting its mission
- Operations, effective and efficient use of its resources
- Reporting, reliability of reporting
- Compliance, compliance with applicable laws and regulations.

Table 4: ERM encompasses eight interrelated components as defined by COSO (2004):

Internal Environment	The internal environment encompasses the tone of an organisation, and sets the basis for how risk is viewed and addressed by an entity's people, including risk management philosophy and risk appetite, integrity and ethical values, and the environment in which they operate.
Objective Setting	Objectives must exist before management can identify potential events affecting their achievement. Enterprise risk management ensures that management has in place a process to set objectives and that the chosen objectives support and align with the entity's mission and are consistent with its risk appetite.
Event Identification	Internal and external events affecting achievement of an entity's objectives must be identified, distinguishing between risks and opportunities. Opportunities are channelled back to management's strategy or objective-setting processes.
Risk Assessment	Risks are analyzed, considering likelihood and impact, as a basis for determining how they should be managed. Risks are assessed on an inherent and a residual basis.
Risk Response	Management selects risk responses – avoiding, accepting, reducing, or sharing risk – developing a set of actions to align

	risks with the entity's risk tolerances and risk appetite.
Control Activities	Policies and procedures are established and implemented to help ensure the risk responses are effectively carried out.
Information and Communication	Relevant information is identified, captured, and communicated in a form and timeframe that enable people to carry out their responsibilities. Effective communication also occurs in a broader sense, flowing down, across, and up the entity.
Monitoring	The entirety of enterprise risk management is monitored and modifications made as necessary. Monitoring is accomplished through ongoing management activities, separate evaluations, or both.

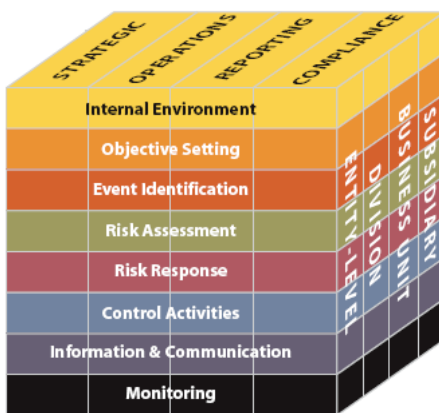


Figure 6 The relationship between objectives, components and organisation

One of the challenges is to establish comparable risk assessment results providing support for trade-off decisions. ERM is in operation in different industries. For aviation the developments are ongoing and sponsored by IATA. Further research is needed and from a resilience perspective it is an promising development.

## 9 CONCLUSIONS

Many resilience engineering concepts require a compatible SMS (Hollnagel, Woods, Leveson 2004). This SMS in development stems from the same paradigm as resilience engineering. Important concepts have been identified but much work still has to be done.

The regulators have set their requirements for SMS's. Only few airlines have the theoretical knowledge and funding to fill the requirements with science based methods, classifications and models to get the most out of their SMS. Both the SMS (re)design and resilience engineering developments are ongoing in parallel and should be linked to produce valid, effective and practical SMS methods.

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