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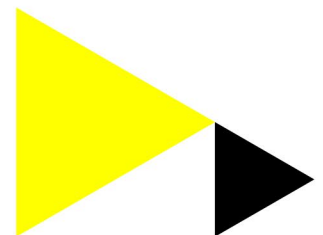
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# Effectiveness of Risk Controls as Indicator of Safety Performance

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## Abstract

The objective of the study described in this paper is to define safety metrics that are based on the effectiveness of risk controls. Service providers define and implement such risk controls in order to prevent hazards developing into an accident. The background of this research is a specific need of the aviation industry where small and medium-sized enterprises lack large amounts of safety-related data to measure and demonstrate their safety performance proactively. The research department of the Aviation Academy has initiated a 4-year study, which will test the possibility to develop new safety indicators that will be able to represent safety levels proactively without the benefit of large data sets. As part of the development of alternative safety metrics, safety performance indicators were defined that are based on the effectiveness of risk controls. ICAO (2013) defines a risk control as “a defence with specific mitigation actions, preventive controls or recovery measures put in place to prevent the realization of a hazard or its escalation into an undesirable consequence”. Examples of risk controls are procedures, education and training, a piece of equipment etc. It is crucial for service providers to determine whether the introduced risk controls are indeed effective in reducing the targeted risk. ICAO (2013) describes the effectiveness of risk control as “the extent to which the risk control reduces or eliminates the safety risks”, but does not provide guidance on how to measure the effectiveness of risk control. In this study, a generic metrics

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for the effectiveness of risk controls based on their effectiveness was developed. The definition of the indicators allows, for each risk control, derivation of specific indicators based on the generic metrics. The suitability of the metrics will subsequently be tested in pilot studies within the aviation industry.

Key Words: Risk Controls; Risk Controls' Effectiveness; Safety Performance

## 1 Introduction

Safety is typically managed through a risk management cycle which includes the stages of hazard identification, risk assessment, risk mitigation and risk monitoring. Under this concept, risk mitigation or elimination is achieved through the introduction of risk controls of various types (e.g., procedures, technology, training), depending on the available resources and the degree of desired control over risks (ICAO, 2013; Kaspers et al., 2016a). According to ICAO (2013), safety assurance includes the process of validating the effectiveness of safety risk controls. However, no further guidance is provided on how the effectiveness of safety risk controls can be measured.

The objective of the research presented in this paper is to explore safety performance indicators (SPIs) that are based on the effectiveness of risk controls. The SPIs are intended to be used in the safety management cycle of aviation organisations, with an emphasis on medium and small-sized companies.

The work presented in this paper was conducted in the context of the research project 'Measuring Safety in Aviation – Developing Metrics for Safety Management Systems', which responds to specific needs of the aviation industry where Small and Medium Enterprises (SME)<sup>†</sup> lack large amounts of safety-related data in order to measure and demonstrate their safety performance proactively (Aviation Academy, 2014). The aim of the study is to identify ways to measure operational safety without the benefit of large amounts of safety outcome data. During the first phase of the project, the research concluded to the following findings:

- State-of-art academic literature, (aviation) industry practice, and documentation published by regulatory and international aviation bodies jointly suggest that (a) safety is widely seen as avoidance of failures

<sup>†</sup> The category of micro, small and medium-sized enterprises (SMEs) is made up of enterprises which employ fewer than 250 persons and which have an annual turnover not exceeding EUR 50 million, and/or an annual balance sheet total not exceeding EUR 43 million (EC, 2003).

and is managed through the typical risk management cycle, (b) safety metrics can be, conventionally, split in two groups: safety process metrics and outcome metrics, (c) there is a lack of standardization across the aviation industry regarding the development of safety metrics and the use of specific quality criteria for their design, and (d) there is limited empirical evidence about the relationship between Safety Management System (SMS)/safety process and outcome metrics, and the link between those often relies on credible reasoning (Kaspers et al., 2016a).

- Results from surveys to 13 aviation companies (i.e. 7 airlines, 2 air navigation service providers and 4 maintenance/ground service organizations) showed that (a) current safety metrics are not grounded in sound theoretical frameworks and, in general, do not fulfil the quality criteria proposed in literature, (b) a few, diverse and occasionally contradictory monotonic relationships exist between SMS process and outcome metrics (Kaspers et al., 2016b, 2016c).

## 2 Literature review

### 2.1 Views on safety risk control

ICAO's Safety Management Manual (ICAO, 2013) uses the term 'safety risk control' without defining it. ICAO used the 'safety risk control' interchangeably with the term 'defences' which is defined as "specific mitigating actions, preventive controls or recovery measures put in place to prevent the realization of a hazard or its escalation into an undesirable consequence" (ICAO 2013). The Federal Aviation Administration (FAA) defines risk controls as "strategies or tools that reduce, mitigate or eliminate the probability of occurrence, the severity of the hazard and/or the exposure of people and equipment to the risk" (FAA, 2000).

No common definition of the term risk control has been found in the literature reviewed although different aspects of the term have been discussed (De Dianous and Fievez, 2006; Duijm, 2009; Neogy et al., 1996; Reason, 1997; Sklet, 2006; Svenson, 2000; Trobjevic, 2008). Literature shows that there is no universal and commonly accepted definition of these terms and that different terms with similar meaning are being used (barrier, safeguards, safety barrier, a layer of protection, a protective layer, risk control, defences, etc.).

Although the definitions are slightly diverse, a common feature in the definitions is that risk control is related to a hazard, an energy source or an

event. The verbs *prevent*, *control* and *mitigate* are also frequently used in describing the function of risk control. According to Hollnagel (2008), a distinction in terminology for risk controls has to be made regarding what risk controls do, their purpose or function, and what risk controls are (i.e., the ways in which they achieve their purpose). De Dianous and Fievez (2006) complement this by stating that risk control functions are the “what” needed to assure or increase safety, and the risk control systems are the “how” to implement the risk control functions.

Classification of risk control functions and risk control systems may be relevant because it is suggested that different classes of risk control functions and systems may have different levels of effectiveness, as described in the next sections.

## 2.2 Classification of risk control functions

It may seem obvious that the most effective way of dealing with an identified risk is the elimination of the risk. However, a risk-free environment in aviation is not possible as human activities or human-built systems cannot be completely free of hazards and associated risks (ICAO, 2013).

Lees (2012) distinguishes between hazard prevention, hazard control and hazard mitigation as conceptual means to control risk. Sklet (2006) concludes that risk controls, which could be physical and/or non-physical, are means to prevent, control or mitigate undesired events or accidents. Rausand (2013) distinguishes three functions of risk controls: prevention, control or mitigation. Brewer and List (2004) use the terms preventive, detective and reactive to describe the functions of risk control. Preventive seeks to ensure the adverse effect never materialises. Risk controls with a detective function identify when some event or events have occurred that could lead to a materialisation of an adverse occurrence and invoke appropriate actions to arrest or mitigate the situation. A reactive risk control identifies the adverse effect that has occurred and invokes appropriate actions to recover or mitigate the situation. This is similar to the categorization of risk control functions used by ICAO (2013), where the terms avoidance, reduction and segregation of exposure cover the same definitions. The classifications for the function of a risk control used in a research study aimed at risk assessment in the context of the Seveso II Directive consist of four main categories described by the verbs ‘to avoid’, ‘to prevent’, ‘to control’ and ‘to protect’ (ARAMIS, 2004).

Trbojevic (2008) approaches the classification of risk control functions based on their effectiveness and uses the terms technical, human/organisational and fundamental (management of change, procedural reviews,

corporate audit, etc.), where 'technical' can prevent the risk, and this is the most effective, and 'fundamental' has low effectiveness.

### 2.3 Classification of risk control systems

The risk control system describes the means by which the risk control functions are carried out (Hollnagel, 2008). Sklet (2006) presents a similar description by stating that the risk control system is a system that has been designed and implemented to perform one or more risk control functions. The system thus describes how a risk control function is realised or executed. ICAO (2013) states that risk control systems could fulfil the risk control function by technology, training or operational procedures. Kang et al. (2016) distinguish between technological, organizational and personnel controls. Reason (1997) uses the terms 'hard' and 'soft' to distinguish between technical and non-technical risk controls. A similar classification is made by Wahlstrom and Gunsell (1998) by differentiating between physical, technical and administrative risk controls. Physical controls are incorporated in the design of construction; technical controls are initiated if a hazard is realized and administrative controls are incorporated in administrative systems and procedures.

Hollnagel (2004) classifies risk controls based on their nature and order of suggested effectiveness into material or physical controls, functional controls, symbolic controls and incorporeal controls. Material or physical controls are controls that physically prevent an action from being carried out or an event from a taken place and are considered most effective. Function controls work by constraining the action to be carried out. Symbolic controls require an act of interpretation in order to achieve its purpose, hence an "intelligent" agent of some kind that can react or respond to the risk control. Incorporeal controls are not physically present or represented in the situation but depending on the knowledge of the user in order to achieve its purpose, and are considered least effective.

According to Manuele (2006), risk controls taken to attain an acceptable risk level are more effective when they follow a prescribed hierarchy of controls. The "hierarchy of control sets forth a way of thinking about taking actions in a feasible order of effectiveness to reduce risks" (Manuele, 2006, p. 186). Depending on the hazard there may be more than one action or strategy applicable. Manuele (2006) proposes the following hierarchy of controls:

- Design the hazard out – modify the system. This includes hardware/software systems involving physical hazards as well as organisational systems.

- Physical guards or barriers – reduce exposure to the hazard or reduce the severity of consequences.
- Warnings, advisories, or signals of the hazard.
- Procedural changes to avoid the hazard or reduce likelihood or severity of the associated risk.
- Training to avoid the hazard or reduce the likelihood of associated risk.

For occupational health and safety, a similar hierarchy of controls, with the most effective on top, is available (OSHA 2016):

- Elimination, physically removing the hazard,
- Substitution, replacing the hazard,
- Engineering control, isolate people from hazards,
- Administrative controls, change the way people work,
- Personal protection equipment (PPE), protect the worker with PPE.

## 2.4 Monitoring performance of a risk control

According to ICAO, performance of risk controls refers to effectiveness (i.e., the extent to which the alternatives reduce or eliminate the safety risks), cost/benefit (i.e. the extent to which the perceived benefits of the mitigation outweigh the costs), practicality (i.e. the extent to which mitigation can be implemented and how appropriate it is in terms of available technology, financial and administrative resources, legislation and regulations, political will, etc.), acceptability (i.e., the extent to which the alternative is consistent with stakeholder paradigms), enforceability (i.e., the extent to which compliance with new rules, regulations or operating procedures can be monitored), durability (i.e., the extent to which the mitigation will be sustainable and effective), residual safety risks (i.e., the degree of safety risk that remains subsequent to the implementation of the initial mitigation and which may necessitate additional risk controls) and unintended consequences (i.e., the introduction of new hazards and related safety risks associated with the implementation of any mitigation alternative) (ICAO 2013).

Neogy et al. (1996) use the terms effectiveness and reliability in order to describe how successful controls are in providing protection. Hollnagel (2008) presents a set of performance criteria that address various aspects of barrier quality: effectiveness or adequacy, resource needs, robustness, delay in implementation, applicable to safety-critical tasks, availability, evaluation and

independence on humans. The ARAMIS user guide uses effectiveness, response time and level of confidence as criteria for evaluating the performance of risk controls (ARAMIS, 2004). Sklet (2006) recommends characterizing the performance of risk controls with functionality/effectiveness, reliability/availability, response time, robustness and triggering event or condition. Sklet also notes that not all attributes are relevant or necessary in order to describe control performance.

### 3 Indicator design

The definition of effectiveness is “the degree to which something is successful in producing the desired outcome” (OED, 2017). In other words, the effectiveness of a risk control provides information on how many times the risk control is addressed in tackling a particular hazard or risk and how many of these times the risk control performs according to the desired outcome of the specific risk control. A generic indicator is developed based on this definition of effectiveness (Muns, 2017):

*The ratio between the number of times a risk control is challenged and the amount of times the risk control achieves a successful<sup>‡</sup> outcome.*

The effectiveness of a risk control provides information on how many times the risk control is addressed in tackling a particular hazard or risk and in how many of these cases the risk control performs successfully. The following metrics have been developed to determine the performance of risk controls:

$$1 - \frac{\text{number of failures of the control when the challenged}}{\text{number of occasions the control was challenged}} \quad (1)$$

$$1 - \frac{\text{number of failures of the control when the tested}}{\text{number of occasions the control was tested}} \quad (2)$$

$$1 - \frac{\text{number of unwanted events after control was implemented per unit of time}}{\text{number of unwanted events before control was implemented per unit of time}} \quad (3)$$

These metrics are listed in preferential order with the most preferred on top. A failure of risk control is defined as a failure to result in the specific desired outcome of the specific risk control. Because for some risk controls it may not be possible to observe if it is challenged, equations 2 and 3

‡ Successful is according to the specific desired outcome of the specific risk control.



are provided. Equation 2 relates to dedicated tests of the risk control (e.g. testing of the fire alarm during a fire drill), while equation 3 compares situations before and after implementation of risk control. For all three metrics it is necessary to have an unambiguous description of the risk control as well as a description of the hazards(s) that the risk control must mitigate. It is also necessary to define what constitutes a failure of the risk control.

### 3.1 Practical steps for application

#### 1) Describe the risk control

Preferably the organisation already has a list of risk controls that are monitored in the context of the safety management system. If this is the case, it is advisable to use the descriptions of the risk controls as they are on the list. If the organisation does not have a list of risk controls, the first step is to identify which controls are in place to reduce safety risks. The risk control must be described as precisely as possible. The better the description, the easier it will be to gather data on the effectiveness of the risk control.

#### 2) Determine how to identify a failure of the risk control

A failure of a risk control may not necessarily result in a safety occurrence as there may be other controls in place to provide additional protection. For example, a failure of air traffic control to provide minimum separation between two aircraft may not necessarily result in a conflict as the pilots may be able to see each other and maintain separation without ATC instructions. It is therefore important to consider how a failure of the risk control can be identified. Try to look for failures of the specific risk control under consideration instead of more general safety occurrences.

#### 3) Determine whether it is possible to identify a challenge to the risk control

A 'challenge' of risk control is a situation in which a risk control is supposed to work. For instance, a hand-held fire extinguisher carried in the cabin of an aircraft is a control against small fires in the cabin. A challenge of the risk control is an attempt to use the extinguisher to put out a fire in the cabin.

#### 4) Determine whether it is possible to test the risk control

When it is impossible or impractical to determine if a risk control is challenged, it may be necessary to calculate the effectiveness of the risk control from equation 2, which means that tests of the risk control are considered. Safety critical systems are often tested periodically, and these test results can be used to estimate the effectiveness of the risk control. As an example, storm surge barriers are essential risk controls to prevent flooding of large parts of the Netherlands in case of severe weather conditions. Because these severe weather conditions are quite rare, and because a failure of a storm surge barrier is unacceptable, they are tested once a year during the summertime, when severe weather conditions that would require a closure of the barriers are least likely. A test, in this case, involves a full closure of the barrier. When it is not possible to determine if a risk control is challenged and testing of the risk control is also impractical, equation 3 should be used.

#### 5) Select a suitable time period

The number of times a risk control is challenged, and the corresponding number of failures of the risk control, can vary widely across different types of risk controls and different organisations. The statistical robustness of the calculated effectiveness depends on these numbers. If no challenges of risk control are observed, the effectiveness cannot even be calculated according to equation 1. The time period must, therefore, be selected such that it is expected that the risk control will be challenged at least several times. In practice, of course, a balance must be found between the size of the sample and the length of the time period.

#### 6) Collect data

Ideally, the data required to calculate the effectiveness are already documented in the context of the safety management systems or quality management system.

#### 7) Calculate risk control effectiveness.

Calculate the risk control effectiveness for the selected risk controls according to equation 1, 2 or 3, whichever is most suitable.

## 4 Examples

### 4.1 Airline

Windshear is a known hazard for aircraft, and many airlines have equipped their aircraft with reactive wind shear detection systems. A reactive wind shear system will provide a warning after penetration of a wind shear area. A wind shear condition is detected using comparisons of angle-of-attack, IRS accelerations, and air data computer airspeed. Annunciation is typically by means of a red wind shear light or displays text and a voice message ("WIND SHEAR WIND SHEAR WIND SHEAR"). Reactive wind shear systems are often integrated into TAWS (Mode 7). Some types of wind shear systems use the Flight Director (FD) to provide guidance regarding the appropriate escape manoeuvre.

The flight crew is expected to respond to a wind shear warning by carrying out a wind shear escape manoeuvre as described in the company operating procedures.

The main actions in the response procedure for a reactive wind shear warning are typically<sup>§</sup>:

- Disconnect autopilot
- Press either TO/GA switch
- Apply maximum thrust
- Disconnect auto throttle
- Roll wings level
- Rotate toward an initial pitch attitude of 15<sup>\*\*</sup> degrees
- Retract speed brakes
- Follow flight director TO/GA guidance, if available.

The standard operating procedure for a wind shear warning is risk control. In order to determine the effectiveness of this risk control, it is necessary to know how many times the risk control is challenged within a particular time period, and how many times the risk control failed, i.e. many times the risk control did not result in the desired outcome. In this case, the risk control challenge is the activation of the wind shear warning, and the desired outcome is the correct execution of the procedure.

§ For aircraft equipped with FD Windshear Escape Guidance; the main actions are to apply maximum thrust and follow the FD.

\*\* The initial pitch target depends on the aircraft type and is not always mentioned in the procedure. 15 degrees is considered a representative value for transport category aircraft.

Data to calculate the effectiveness of the wind shear procedure can be obtained from the airline's flight data monitoring program. Activation of the wind shear warning is easily retrieved from flight data. To determine if this is followed by the correct procedure is necessary to define the correct procedure in terms of flight data. The airline may, for instance, define the profile for an appropriate response to a reactive wind shear warning as follows:

- 5 seconds after the first WINDSHEAR warning the thrust setting should be within 10% of maximum thrust.
- 12.5 seconds after the first WINDSHEAR warning the pitch attitude should be within 20% of the initial pitch target<sup>††</sup>.

The response time of the first item of the appropriate response profile is based on the initial reaction time of 5 seconds. The response time of the second item is derived by assuming a pitch rotation speed of 2 degrees per second. With a 5 second initial reaction time and assuming an initial pitch attitude of 0 degrees this means it takes 12.5 seconds to reach a pitch attitude of 15 degrees.

To further illustrate the example, it is assumed that a large international airline collects the following data for a single calendar year:

**Table 1** Example Data from an Airline

Total Number of Flights	Number of Wind Shear Warnings	Number of Appropriate Responses	Number of Inappropriate Responses
208,163	94	65	29

In this example, the number of challenges of the risk control is 94, and the number of failures of the risk control is 29. The effectiveness is calculated according to equation (1):  $1 - (29/94) = 0.69$ . The airline may then track this effectiveness over a number of years to monitor a change in effectiveness, or it may compare the effectiveness across types of aircraft within the fleet.

## 4.2 Airport

The traditional vegetation mosaic at airports constitutes large areas of grass. Although aesthetically appealing, easy to maintain and functional, the grass is likely the dominant bird-attracting feature at airports

<sup>††</sup> Aircraft equipped with FD Windshear Escape Guidance: 15 seconds after the first WINDSHEAR warning the pitch attitude should be at or above 5 degrees.

(Transport Canada 2004). Because birds are a hazard for aircraft, airports employ various measures to reduce the local bird population. Among bird strike specialists it is generally agreed that making the runway environment unattractive for birds is a better approach than relying on corrective actions that expel birds. Since its successful introduction in the UK in the seventies, the long grass policy (LGP) has been considered the standard in grassland management for runway environments and is widely recommended by National Aviation Authorities (Dekker 2000). Allowing grass to grow longer serves several purposes: long, dense grass makes it more difficult for birds to find food such as worms and insects, longer grass reduces birds' visual contact with surrounding environments and inhibits their ability to detect potential predators.

However, the long grass policy may not be equally effective at all airports, depending on the types of birds that may be present at the airport. Therefore, an airport may want to determine if LGP is effective risk control. In this case, the number of times the risk control is challenged is impossible to determine. Testing of the risk control is also not possible, and therefore the risk control effectiveness must be calculated by counting the number of unwanted events per unit of time before and after implementation of the risk control. In this case, the unwanted event is the presence of birds at the airport. The airport can conduct regular bird counts at specific observation points. Because of possible seasonal effects, it is important that such counts are conducted over at least a full calendar year. Morgenroth (2005) describes the results of such bird counts at Dresden airport, where the average was 7.3 birds per observation point for short grass ( $\leq 10$  cm) and 2.49 birds per observation point for long grass with a height of 10-30 cm. The total observation period was two years. The effectiveness of long grass management at this airport is calculated according to equation (3):  $1 - (2.49/7.3) = 0.66$ .

## 5 Industry review and next steps

The proposed metrics for the effectiveness of risk controls were distributed among academia and industry with a request to provide feedback. The material constituted of a one-page description of the background, the proposed indicators and a note on information that must be available in order to apply the metrics. Reviewers were asked to assess the proposed indicators according to quality criteria that were developed in an earlier part of the study (Kaspers et al., 2016b). Comments were received from

eight organisations (three airlines, two aviation consultants, a maintenance organisation, a ground support organisation and an airport). In general, the response was positive in the sense that the organisations indicate that the metrics as defined can provide a worthwhile contribution to safety management. However, several respondents expressed concern about the availability of sufficient information, especially for smaller enterprises. It was also indicated that these metrics are easier to use if the organisation utilises a bow tie method or something similar as the barriers would already be defined.

As a next step, the metrics description will again be distributed among aviation service providers with a request to apply the metrics. The purpose is to test the practical applicability and to validate an association between the metrics and safety performance.

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