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Risk and Uncertainty in Aviation: A Thorough Analysis of System Vulnerabilities

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Abstract**—**Hazard assessment and risks quantification are key components for estimating the impact of existing regulations. But since regulatory compliance cannot cover all risks in aviation, the authors point out that by studying causal factors and eliminating uncertainty, an accurate analysis can be outlined. The research debuts by making delimitations on notions, as confusion on the terms over time has reflected in less rigorous analysis. Throughout this paper, it will be emphasized the fact that the variation in human performance and organizational factors represent the biggest threat from an operational perspective. Therefore, advanced risk assessment methods analyzed by the authors aim to understand vulnerabilities of the system given by a nonlinear behavior. Ultimately, the mathematical modeling of existing hazards and risks by eliminating uncertainty implies establishing an optimal solution (i.e. risk minimization).

Keywords**—**Control, human factor, optimization, risk management, uncertainty.

I. INTRODUCTION

THE palette of threats on aviation safety, the dynamic aspects regarding risk and its evolution reflect in the magnitude of the consequences. Considering the volume of data collected and determining system status, an analysis of the threats will highlight previous experiences and practices and will impose treating the effects, and developing probabilistic studies useful for risk reduction strategies.

A systematic review of all subsystems will establish interdependencies between them and safety measures to eliminate or reduce risk, being able to prevent about 86% of property damage or 90% of the events that have repercussions such as injuries.

In order to establish a correct analysis, a good understanding of different terms and delimitation between notions/concepts is very important. For example, 'hazard' is a term often misunderstood and therefore incorrectly used, the error regards a dependence on human factor or its connection with possible consequences of events. This being noted, hazard reflects a violation/an exceeding of the required/imposed safety conditions, so it represents a cause, not an effect [1]. It is therefore imperative to identify hazards before establishing any actions meant to eliminate the possibility for accidents/incidents to produce.

TABLE I
HAZARD IDENTIFICATION [17]

Level 1	Level 2	Level 3
Procedures used for voluntary hazards/ threats reporting by all employees.	Establishing clear distinction between hazards and consequences.	Procedures used to identify hazards/threats from internal event investigation reports for follow up risk mitigation.

Such undesirable conditions (i.e. hazards) reflect possible latent factors which may lead to unsafe events and consequences; therefore, organizations must evaluate threats and take actions in order to mitigate risks [17]. Thus, correcting the above stated misunderstandings will emphasize the fact that risk is a consequence of hazard. As is known, risk represents a future impact of hazard that is not controlled/eliminated, and therefore, it can be defined as uncertainty created by a threat/hazard; this way, the level of uncertainty can be established [1].

TABLE II
RISK MITIGATION [17]

Hazard (H)	Preventive control (PC)	Escalation factor (EF)	Escalation control (EC)
H	PC1 (Existing)	EF (Existing)	EC1 (Existing) EC2 (New)
	PC2 (Existing)	EF1 (Existing) EF2 (New)	EC (New) EC (New)
	PC3 (New)	EF (New)	EC (New)

Risk is also defined by the vulnerability of a system, which is a status indicator, a reaction to the critical conditions affecting the proper functioning and that triggers certain baleful reactions. Reported to the concepts above (i.e. hazard and vulnerability), an expression of risk can be noted as:

$$R = f(H, E, V) \tag{1}$$

Therefore, risk is a function of three elements: H – hazard, E - elements subject to risk, V- vulnerability.

FAA's perspective on risk definition gathers hazard and uncertainty concepts: "Risk is the future impact of a hazard that is not controlled or eliminated. It can be viewed as future uncertainty created by the hazard" [7].

Another worthy of attention, confusion regards the concept of "uncertainty" because it is often confused with risk. It must be underlined that, through a mathematical approach, it can be established that uncertainty is not a sufficient condition for the existence of a risk [1]. The attention on the definition of risk will carry a clear delineation of terms, i.e. risk refers to the existence of consequences that need to be analyzed.

The manner of characterizing risk using hazard and

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uncertainty notions was extensively analyzed by Bedford and Cooke in 1996. The two definitions refer to the source of danger, outlining that uncertainty can be quantified by probability [2]. From the perspective of information carried, the line between the concepts of risk and uncertainty can be determined as follows:

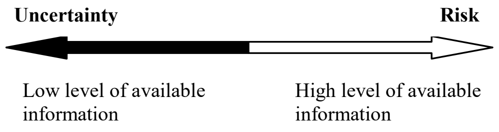

Fig. 1 Available information for risk and uncertainty

A low level of available real data (knowledge) or even the lack of information results in epistemic uncertainty, which is important for both qualitative and quantitative evaluation.

In order to define risk based on existing knowledge or data, one must take into account that different risk types may arise either if there is uncertainty about the outcome of a certain event or its emergence is uncertain although the effects might be known. Surely, a simpler analyzed case is when both the event and its effect are unsure/doubtful.

Since the overall image on risks is influenced by the quality and clarity of the information, uncertainty, and therefore the procedures for identifying and fixing the values of risk, may present variations that must be within the limits of the available information/data. The following table contains such an example:

TABLE III
PROBABILITIES/CONSEQUENCES CORRESPONDING TO DIFFERENT LEVELS OF AVAILABLE INFORMATION

Level of information	Probability	Consequences
1 (Certainty)	Known	Known
2	Known	Known
3	Unknown	Known
4 (Uncertainty)	Unknown	Unknown

The probability considered for a maximum of information corresponding to level 1 (certainty), is estimated with the value 1, which is the probability for a safe event. Therefore, the consequences of the event are known exactly because expected values and limits are calculated based on quantification of the factors involved using complex methods.

II. DEVELOPMENT OF SCENARIO AND RISK ANALYSIS

In the aeronautical field, control must be directly proportional to safety levels; therefore, the probability to encounter a lack of information/knowledge in processes analyzed must be minimized. Risks cannot be completely excluded in aviation, even with the possession of full information, this is a field characterized by risks, but it should not be characterized by uncertainty [1].

Confronting effective achievements with actual proposed/anticipated/expected results, aims to maintain certain values and limits where risks can be assigned and classified. The evolution study of design operating performance and system vulnerabilities should be studied in order to facilitate identification, awareness and qualitative analyzes of risk. In addition, quantitative risk assessment has an important contribution to the types of decisions that involve uncertainty (aleatory or epistemic), deviation from standard practice, etc. [15].

A modern definition of risk includes more aspects providing information about the set of scenarios for the accident, analysis on the probability of occurrence/evaluation of an event (risk assessment is therefore compulsory) and determines classes of consequences and their impact. Over the years, authorized bodies in aerospace have offered slightly different approaches on risk definition. The concepts have in common that risk is a combination of undesirable consequences of accident scenarios and the likelihood of these scenarios to produce [1].

Understanding the fundamental notions is useful for indicating gradual processes and different stages needed to identify, evaluate and rank dominant risk contributors.

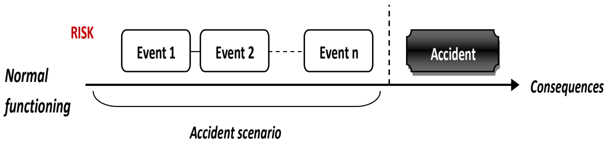

Fig. 2 Accident scenario

Accident scenario modeling tools are based on an inductive logic, and the approach on vertical hierarchy from basic activities to major processes describe sequence diagrams that are suited both for an engineering and managerial approach. Data analysis monitors system performance and is achieved through statistical and graphical tools used to detect safety issues, reflecting the dynamic aspects of risk and its evolution, and uncertainties regarding decision making and human factor.

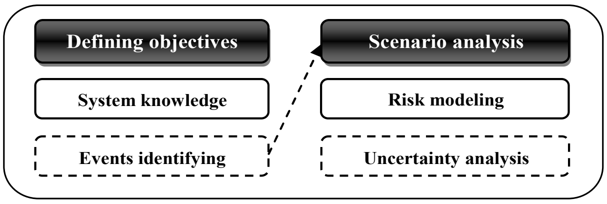

Fig. 3 Data analysis

Scenarios regarding accidents, like the loss of control (LOC-I), which is considered a leading cause of fatalities, have been created based on an analytical generalized approach, and originated from study cases and engineering knowledge.

The evolution of accidents determined by the above mentioned risk category (i.e. loss of control in-flight) and the values recorded for fatal accidents and the numbers of fatalities reported to the overall number of events are shown in Figs. 4 and 5 [13].

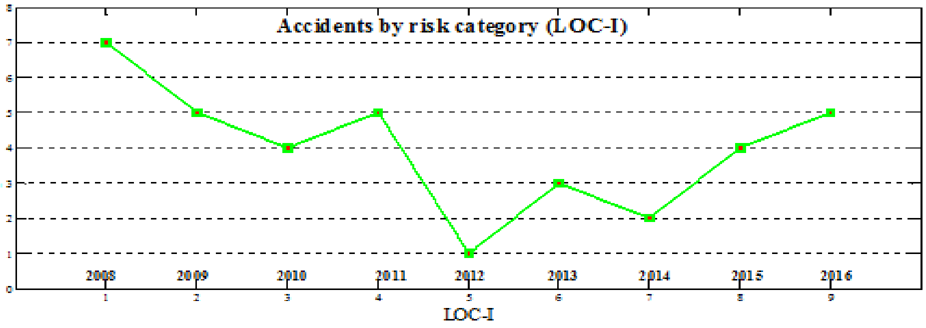

Fig. 4 Accidents by risk category (LOC)

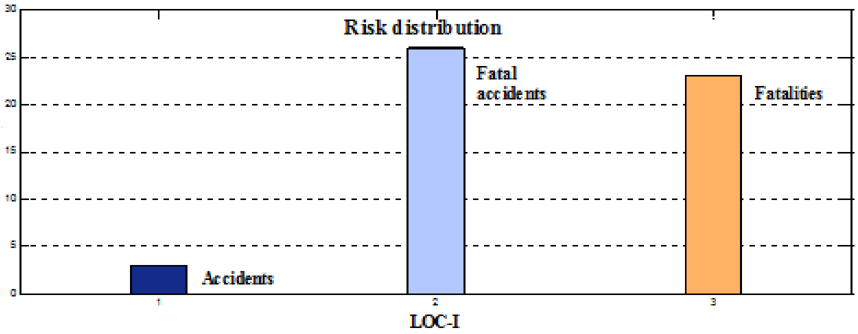

Fig. 5 Risk distribution and relative (LOC-I) risk importance

Another approach to risk management can be achieved through quality assurance, which takes in consideration the fact that losing resources (for example physique, financial, human) can have serious consequences [5].

$$\begin{aligned}&Quality\quad Costs = \\ &Quality\quad Assurance\quad Costs + Nonconformity\quad Costs\end{aligned} \tag{2}$$

Assuring quality in aviation means, at a final level, improving performance and minimizing costs; the need to enhance quality by the continuous monitoring of all activities that might influence/affect proper functioning, might be achieved through coercive actions. In this regard, ISO 9004 Standards for organization planning and control must be applied.

An analysis driven by Professor Reason in 1992, showed that in a three year period, during maintenance inspection, the quality lapses detected (through a frequency of occurrence study), were divided and ranked according to their impact upon the aircraft. The conducted study showed over 120 quality lapses such as omissions (56%), incorrect installations (30%), wrong parts (8%) and other (6%) [16]. Still, such analyses do not reveal the reasons why human factor makes different or particular errors, nor show what influences its performances.

Risk analysis models determine precise examination of the degree of compliance with the requirements of the system and imply the development of a scenario and sustained efforts in assuring quality.

A. Uncertainties Regarding Decision Making and Human Factors

Through an integrated management system, understanding the factors that influence the premises of unsafe actions becomes vital for the process of selecting management strategies for eliminating risk and overcoming the limitations of human performance.

Standards regarding risk management involve a continuous analytical process nature on different levels that enables a proactive approach on program development. Responsibilities regarding safety must be clearly defined so, organized risk management structures must exist as in Fig. 6.

Management decisions establish the methodology and overall context that drives the whole process of the analysis. Decision making is a complex problem in the context of the human factor; one of the elements which generate it, can be the lack of clarity during safety investigations by describing improperly the circumstances and the decisions that led to the accident/incident. Generally, decision making is based on analyses and evaluations of systems performance, equipments, and policies [4].

Uncertainty does not only regard decision making, but also probability risk assessment and reliability aspects, determining therefore the probability of failure/malfunctions and the probability of accidents occurring per flight hour.

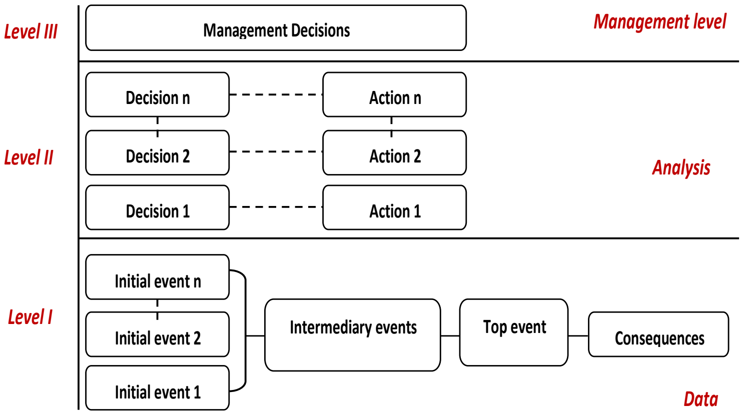

Fig. 6 Levels of analysis

A risk may be considered an element with a measurable probability of deviating from an established plan [8], and one way to define it is through PRA techniques. The probability of individual events is probabilistically modeled, and indications of possible effects/consequences are provided through calculated results.

$$R = P \times S \tag{3}$$

where P – Probability, S – Severity.

TABLE IV
CHARACTERISTICS AND PROBABILITIES FOR PLANNING ERRORS

Function	Type of failure	Characteristics	Probability
Planning	Wrong/Inadequate planning	Improper content	10^{-2}
Planning	Wrong prioritization of activities	Wrong succession of operations	10^{-2}

The probability of human error (related to planning, execution, etc.) is usually accompanied by specific uncertainty assessment. Operational decision errors implies decision-making that is not standardized by operator procedures or regulations that compromises safety in an unnecessarily manner [6].

Another approach to risk factor refers to the occurrence, severity and detection factor; this analysis being followed by the adoption of corrective measures for both severity and effective risk.

$$V_R = f(A,S,D) \tag{4}$$
$$V_R = A \times S \times D$$

where, A - incidence of occurrence, S – severity, D – detection

Surely, regulatory compliance cannot cover all risks in aviation. Sometimes, performance pressures on human factors (not only the flight crew) might originate in/or hide the organization’s poor safety culture. An example of an accident that takes into account the above listed risk factors (i.e. competence, rule violation, knowledge level and operation planning) happened on 14th November, 1988. On a scheduled passenger flight, the Embraer 110P1 Bandeirante twin turboprop aircraft, registered OH-EBA, operating for Wasa Wings, crashed 1 km from Seinäjoki-Ilmajoki Airport (SJY) in Finland, being damaged beyond repair.

TABLE V
OCCURANCE/DETECTION OF RISK FACTOR RELATED TO HUMAN PERFORMANCE

Criterion	Occurrence (%)	Detection (%)
Competence	61	86
Rule violation	27	73
Knowledge level	11	70

The proximate cause of the accident was the pilot’s decision to continue a NDB approach below minimum altitude without the required visual contact with approach lights or the runway and contributory factors were the airline's poor safety culture due to pressures of performance, highlighted by the pilot because of his personality structure [12].

In time, the magnitude of such risks faded away, the probabilities of risk decreasing significantly; nowadays, the accident’s classification Controlled Flight Into Terrain (CFIT) have the following values recorded for scheduled commercial flights on airplanes above 5.7 tones.

According to ICAO Accident-Statistics [13], the relative risk importance and its distribution for CFIT during 2012-2016 is according to Fig. 6.

Vulnerabilies related to continuous technological progress may cause potential disturbances. The interaction between human factor and technological elements determines the system’s behavior and can also be the foundation for uncertainties concerning system environment evaluation. In this regard, for example, the Task Force led by EASA recommended, among others, to establish a robust oversight program on the performance of aero-medical examiners and to implement support and reporting systems, linked to the employer Safety Management System as a result of the 2015 Germanwings crash of an Airbus A320 in the French Alps on 24th March, 2015, which reminded the international aviation community that the medical and psychological conditions of flight crews can have catastrophic outcomes [9]. This particular case falls into the category of planning errors defined by James Reason through the notion of "intention"; classification which is based on identifying if the plan/actions were made as intended, taking into consideration the way they carried on and their results. Surely, the pilot's intention was clear, i.e. to achieve this particular intended outcome (catastrophic accident), as the report of the investigation showed. Understanding unsafe conditions involves knowledge of the environment and the factors involved.

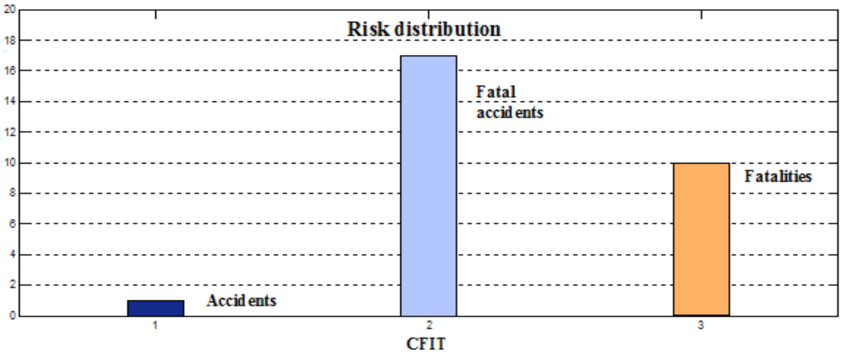

Fig. 7 Risk distribution and relative (CFIT) risk importance

TABLE VI
CHARACTERISTICS AND PROBABILITIES FOR EXECUTION ERRORS

Function	Type of failure	Characteristics	Probability
Execution	Missed action	Omission of operation/Failure to use resources	$3\cdot10^{-2}$
Execution	Wrong action	Wrong/defective execution	$3\cdot10^{-3}$

Mistakes are not the case of execution errors, but actions that were not carried out usually occur at the stage of execution. If the type of failure associated to execution is a wrong action, incorrect application of the rules or the application of the wrong rules may be the case for unfulfilling a plan. According to a classification made by IATA, risks related to execution (i.e. monitor, cross check, etc.) or planning can be reflected in the following Controlled Flight Into Terrain (CFIT) Accident Analysis Report which considers five categories of risks related to human factors [14]:

TABLE VII
CFIT RISK RELATED TO HUMAN FACTOR

Risk type	Value (%)
Monitor/Cross check	38
Overall crew performance	35
Communication environment	12
Leadership	12
Plans stated	12

Decision making must be related to actions taken for problem solving that may require more than an individual responsibility for decision making, but an extended support from the human factor (e.g. the support of all crew members for the decisions taken by the pilot-in-command). Also, the subject of the action that must be achieved may be wrong, in that case, uncertainty may characterize the data held, or the information might be incomplete, unsatisfactory or incorrect, characterized by a $5\cdot10^{-4}$ probability.

TABLE VIII
CHARACTERISTICS AND VALUES FOR EXECUTION ERRORS

Function	Type of failure	Characteristics	Probability
Execution	Action out of sequence	Wrong sequence of operations	$3\cdot10^{-3}$
Execution	Non-synchronization of operations	Delays or actions made in advance	$3\cdot10^{-3}$

From a safety culture perspective, the way to avoid uncertainty regards promoting implementation of regulations, clear guidance and control. So, in the case that some goals are not achieved, it might be assumed there is something wrong with the rules [11]. Building safety levels through a safety culture perspective, implies system knowledge and understanding its vulnerabilities, hazard identification and considering safety responsibility of human factor (like taking actions).

The most powerful system factor affecting organizational design is environmental uncertainty. In highly uncertain environments, rapid response to change and flexibility are needed, as opposed to highly stable environments, where it is desirable to incorporate control and stability for maximum effectiveness [11].

TABLE IX
SAFETY CULTURE CHARACTERISTICS REGARDING INFORMATION HELD [10]

Safety culture characteristics	Poor	Bureaucratic	Positive
Hazard information	Suppressed	Ignored	Actively sought
Dissemination of safety information	Discouraged	Allowed, but discouraged	Allowed

TABLE X
CONVERSION OF RISK MANAGEMENT MODEL REGARDING INFORMATION HELD [11]

Old model	New model
Closely held information	Open communication
Rigid rules	Flexible rules
Fixing former problems	Preventing next accidents

Unlike systems which cannot adapt to unprecedented situations, the human factor can react to unexpected events and easily adapt in different circumstances, but uncertainty regarding failure associated to human factor actions is larger than the estimates associated to equipment or the system. So, safety actions are not based on formal identification of threats and vulnerabilities, they must be implemented after establishing classes of risk and it must imply studies of the stage that can be achieved in minimizing risk.

Implementing barriers should include the identification of vulnerabilities, proper and reliable information analysis, a systems state evaluation (risk assessment), human factor training, strict application of procedures, supervising and control performed by verifications and investigations, and continuous enhancing of safety levels. These actions imply the increase of performance and technological development.

III. Mathematical Modeling of Risks: Establishing an Optimal Decision

Ensuring a system's safety levels, where performance is increasing becomes a central point, the consequence of understanding this issue leading to performing studies to identify and then minimize risk based on methods of determining the optimal solution.

Minimizing risks starts from understating consequences/losses and implies reducing the vulnerabilities of the systems. As a second objective, one must consider dealing with the ability to adapt the factors involved in the operation of the system, i.e. factors that exhibit variations in operating and which are usually a response to external conditions [1]. Extending the analysis of basic factors is achieved through an in-depth study of the preconditions for unsafe actions.

Mathematical modelling of existing hazards and risks starts by eliminating uncertainty, identifying significant parameters, numerical evaluation of results through different procedures, thus it will demonstrate the effectiveness of risk assessment and continuous management.

Risk assessment tools are built on probability theory as an indicator of the realization of different causal factors. Considering events compatibility, the risk probability is established by the Poincaré relation:

$$P(A) = P\Big(\bigcup_{i=1}^{n}(A_i)\Big) = \sum_{i=1}^{n} P(A_i) - \sum_{j=2}^{n}\sum_{i=1}^{j-1} P(A_i \cap A_j) + \\ + \sum_{k=3}^{n}\sum_{j=2}^{k-1}\sum_{i=1}^{j-1} P(A_i \cap A_j \cap A_k) + (-1)^{n+1} P\Big(\bigcap_{i=1}^{n}(A_i)\Big) \tag{5}$$

While the probability of the reunion of independent events is:

$$P(A) = P\Big(\bigcup_{i=1}^{n}(A_i)\Big) = \sum_{i=1}^{n} P(A_i) \tag{6}$$

The intersection probability of compatible events uses conditional probabilities:

$$P(A) = P\Big(\bigcap_{i=1}^{n}(A_i)\Big) = \\ P(A_1)\cdot P(A_2 / A_1)\cdot P(A_2 / A_1 \cap A_2)\cdots P\Big(A_n / \bigcap_{i=1}^{n-1}(A_i)\Big) \tag{7}$$

And for incompatible events:

$$P(A) = P\Big(\bigcap_{i=1}^{n}(A_i)\Big) = \prod_{i=1}^{n} P(A_i) \tag{8}$$

$$A_1 \cap A_2 \cap \ldots \cap A_n = \varnothing \tag{9}$$

Optimization processes involve the development of a mathematical model that follows the next steps:

- Establishing the mathematical expression of the function to be optimized.
- Numerical determination of the minimum value or levels of risk.

Determining the optimal value of risk (form the class of acceptable risks) is a process treated as a problem with nonlinear restrictions [3]. Surely, optimization must have a practical side, but also one based on applying mathematical methods.

Considering the minimization of the objective function f

$$f : \mathbb{R}^n \to \mathbb{R} \tag{10}$$

in report to n variables $x_1, x_2, \ldots, x_n$

$$f(x) = f(x_1, x_2, \ldots, x_n) \tag{11}$$

The way to minimizing risk lies in finding the optimal values $x_1^*, x_2^*, \ldots, x_n^*$ for the function's variables. Whereas accidents represent a sum of several causes and analyzed risks may be multiple, from various classes and levels, the function in question has the next variables: $x_1, x_2, \ldots, x_n$.

The restrictions applicable to the function's variables have the following aspect:

$$g_j(x) \le 0 \\ j = 1, 2, \ldots, r \tag{12}$$

Regarding a problem with restrictions, the way to approach it is by generating admissible directions p that create angles higher than 90° with all the restriction's gradients [18].

$$g_i{}'(x)^T p < 0 \\ i = 1, 2, \ldots, r \tag{13}$$

The relation above must be accomplished in order to generate admissible directions p, but since those directions must be also usable, another condition must be form satisfied; the admissible directions must admit the decreasing of the criterion function $f(x)$ [18]. Therefore, the following relation must be provided/assured:

$$f_x^T p < 0 \qquad (14)$$
$$f_x^T p \equiv f'(x)^T < 0$$

Taking into account a variety of factors, determining the best solution from a set will meet the management objectives to minimize risk. Treating risks associated with aviation activities also means maximizing safety levels; this approach involves low tolerance to accidents. Risk studies establish, in addition the targets of the analysis, limitations and restrictions on parameters taken into account, so that analytical results are necessary and sufficient, therefore relevant.

After identifying risks related to human performance, the resources used to change causal factors can provide/become a way to optimize risks and develop an accurate safety culture. The measures taken in response to observed shortcomings are meant to correct different risk factors.

For the correction of human errors, statistics revealed that the way to optimize knowledge levels and competence was achieved by imposing the right mechanisms of safety information culture in an organization; so by following rules, transformations of the risk factors concerned were spectacular [19].

Although the process implies optimization of the functions in both cases, the quantitative analysis of risks has mirrored maximum values in competence and knowledge level while minimizing the aspects regarding rule violation.

TABLE XI
CORRECTION OF HUMAN FACTOR RISK (I.E. RULE VIOLATION)

Criterion	Correction (%)
Rule violation	50

TABLE XII
CORRECTION OF HUMAN FACTOR RISK (I.E. COMPETENCE AND KNOWLEDGE LEVEL)

Criterion	Correction (%)
Competence	70
Knowledge level	25

Risks usually indicate a particular safety deficiency in the system or regarding organizational aspects. Sometimes, a significant safety concern will indicate insufficient safety oversight which ensures the effective implementation of applicable ICAO Standards [17]. Safety audits can provide a way to optimize (minimize) risks by identifying potential ones before they could have an impact on safety.

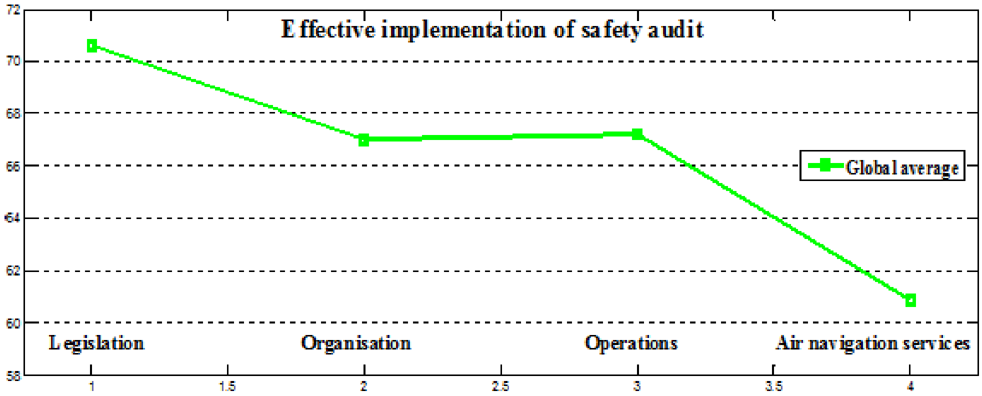

Fig. 8 Effective implementation score of safety audit

An effective Implementation score of the Universal Safety Oversight Audit Programme (USOAP) made by ICAO [17] is shown above.

IV. CONCLUSION

Awareness of risk factors and the ability to restore the situation prior to the occurrence of errors have significant support from advanced technologies; however, these issues may be overshadowed by uncertainties regarding decision making and human factor, as well as the misinterpretation of warnings.

The purpose of establishing system's vulnerabilities and eliminating uncertainties is linked to the decisions to be taken in the context of risk management; it is therefore about balancing reaching the lowest acceptable level of risk and restricting/controlling maximum permitted levels of risk.

By identifying risks, reporting and investigating events, safety systems can establish complex causal factors and provide resources for a change in attitude towards safety, knowing that these aspects depend on developing an accurate safety culture, but mainly on the context in which the accident occurs.

Risk modelling aims to study causal factors and to eliminate uncertainty, in order to outline an accurate analysis; by evaluating all factors involved and understating the consequences, organizations may minimize the vulnerability of the systems. It is therefore essential to apply rigorous mathematical models for risk analysis and risk optimization, since an unsubstantial or formal analysis will reflect in uncertainties regarding prediction of accident probability and in safety analysis.

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