Abstract—This paper addresses the automation of the risk assessment of commercial flights associated with an isolated event or with several events. The overall risk factor is the outcome of fuzzy logic methodology, and is calculated as the sum of the partial risk factors of each event, multiplied by fuzzy coefficients.

The use of fuzzy logic brings a natural representation and an easier understanding of the highly subjective concepts existent in risk assessment. The biggest challenge is to identify for each concept, the relevant variables that best describe it and the way they relate to each other, in order to create a fuzzy set that expresses the relevant human knowledge detained by the risk assessment specialists.

The risk assessment model here proposed is a generic model, and therefore, it can be used in several areas like aviation, finance, health-care, fire prevention, etc… The CalcRisk software developed in the context of this work represents a case study, where this model is applied to the aviation area, being specifically developed for the Flight Safety Department of Transportadora Aérea Portuguesa (FSD-TAP).

Index Terms—Fuzzy Logic, Risk Assessment, Severity

I. INTRODUCTION

The success of every company depends on the risk involved in their own operations and their ability to measure risk factors. Risk assessment is also very important in the aviation area, because in public opinion, hazards are frequently associated with catastrophic events involving life losses or serious injuries. Therefore, there is a constant obligation to assess risk and to act proactively, in order to reduce risk levels and increase the safety of passengers, staff, airplanes and operations.

Because of the high complexity of aviation systems, risk assessment is very often determined by discussions and debates, where the aviation specialists analyze all relevant data that concern an occurrence. This is a somewhat subjective and unreliable process because it depends on ones opinion, and therefore, if the same occurrence is analyzed by other specialists, the risk assessment might be totally different.

The main goal of this paper is to assess risk automatically with the minimum subjectivity possible and obtain consistent results.

There are already some scientific methods applied to risk assessment in its many variants: Monte-Carlo Method [1], Bayesian Networks [2], [3], [4], Stochastic Models [8], Fault/Event Trees [9], [10], Fuzzy Logic [11], etc…

The contribution of this paper is a new quantitative risk assessment method that uses fuzzy logic to determine the weight of each partial risk factor.

II. QUALITATIVE ANALYSIS

A. Probability of Occurrence

To assess the risk of any event, it is necessary to determine its Probability of Occurrence. There are many possible ways to classify this probability, but the most common, is the qualitative classification adopted in [17], as shown in Table I.

<table>
<thead>
<tr>
<th>Qualitative definition</th>
<th>Description</th>
<th>Quantitative definition (per flight hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely improbable</td>
<td>Should virtually never occur in the whole fleet life.</td>
<td>$p &lt; 10^{-9}$</td>
</tr>
<tr>
<td>Improbable</td>
<td>Unlikely to occur when considering several systems of the same type, but nevertheless has to be considered as being possible.</td>
<td>$10^{-9} &lt; p &lt; 10^{-7}$</td>
</tr>
<tr>
<td>Remote</td>
<td>Unlikely to occur during the total operational life of each system but may occur several times when considering several systems of the same type.</td>
<td>$10^{-7} &lt; p &lt; 10^{-5}$</td>
</tr>
<tr>
<td>Occasional</td>
<td>May occur once during total operational life of one system.</td>
<td>$10^{-5} &lt; p &lt; 10^{-3}$</td>
</tr>
<tr>
<td>Frequent</td>
<td>May occur once or several times during operational life.</td>
<td>$p &gt; 10^{-3}$</td>
</tr>
</tbody>
</table>

B. Severity

The Severity is a measure of the damage that an event causes, or may possibly cause, to passengers, crew or airplane. This is an important measure associated with every event and is also classified qualitatively in [17], as in Table II.

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TABLE II: CLASSIFICATION OF SEVERITY

<table>
<thead>
<tr>
<th>Severity</th>
<th>Description</th>
</tr>
</thead>
</table>
| Catastrophic | • Equipment destroyed  
  • Multiple deaths |
| Hazardous | • A large reduction in safety margins, physical distress 
  or a workload such that the operators cannot be 
  relied upon to perform their tasks accurately or 
  completely.  
  • Serious injury or death to a number of people.  
  • Major equipment damage |
| Major | • A significant reduction in safety margins, a 
  reduction in the ability of the operators to cope with 
  adverse operating conditions as a result of increase 
  in workload, or as a result of conditions impairing 
  their efficiency.  
  • Serious incident. |
| Minor | • Nuisance.  
  • Operating limitations.  
  • Use of emergency procedures.  
  • Minor incident. |
| Negligible | • Little consequences |

C. An example of Severity assessment

In the aviation area there are several possible events, but one of the most popular is the event called Ground Proximity Warning System (GPWS). This event is triggered whenever the airplane is getting too close to the ground, Fig. 1(a). According to [26], GPWS depends on the Radio Altitude (RA) and Sync Rate (SR) of the airplane, Fig. 1(b).

In Fig. 1(b) there are two different zones: zone 1 and zone 2. In zone 1 the GPWS system issues visual warnings to inform the pilots that the airplane is approaching the ground.

In zone 2 the GPWS system issues a much serious aural warning “Whoop Whoop, pull up!” indicating the urgency to pull the aircraft up to avoid accident.

In general, one might say that the Severity of GPWS increases as the RA decreases, and also increases as the SR increases, as shown in Fig. 2.

By specifying a numeric scale of 0 to 100 and converting all qualitative classes to appropriate values, the qualitative assessment of Fig. 2 gets converted into the quantitative assessment of Fig. 3.

D. Risk. What is Risk?

The Risk concept is not always easy to understand, and sometimes, it’s easily mistaken with a simple probability.

To better understand Risk, one can consider two hypothetic scenarios: in scenario A there is a person trying to cross a road where there are only bicycles; in scenario B there is the same person trying to cross a road where there are only cars. Considering certain conditions, where the probability of that person being run over is exactly the same in both scenarios, it’s quite obvious that the consequences are much higher in scenario B.

Therefore, the Risk concept is a measure of danger that depends on the Probability of Occurrence and Severity of the events. According to [17], [18], [25], Risk can be classified qualitatively, as shown in Table III.
### Table III: Classification of Risk

<table>
<thead>
<tr>
<th>Probability of Occurrence</th>
<th>Extremely improbable</th>
<th>Improbable</th>
<th>Remote</th>
<th>Occasional</th>
<th>Frequent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catastrophic</td>
<td>R</td>
<td>U</td>
<td>U</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>Hazardous</td>
<td>R</td>
<td>R</td>
<td>U</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>Major</td>
<td>A</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Minor</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>R</td>
<td></td>
</tr>
</tbody>
</table>

Legend: A – Acceptable; R – Review; U – Unacceptable

#### E. The disadvantages of qualitative assessment

**Too much subjectivity** – This type of qualitative assessment is based on one’s opinion, therefore, different specialists have different opinion about the events.

**No guarantee of consistent criteria** – It is not easy for an aviation specialist to apply always the same criteria in a consistent way. Any specialist may apply one criteria in one day and different criteria in the day after, leading to inconsistent risk assessment.

**No differentiation in each class** – This type of qualitative assessment classifies Severity and Risk in qualitative classes, and this way, it’s not possible to compare two events of the same class, to see which one represents the highest Severity or Risk.

**Abrupt transitions between classes** – An event is classified according to its conditions of occurrence. With this type of qualitative assessment, it’s possible that major changes on the conditions of occurrence of an event, don’t make any changes on the event’s Severity or Risk classification. On the other hand, it’s also possible that even the smallest change on the conditions of occurrence of an event, results in a completely different classification of the event’s Severity or Risk. This effect is visible in the discontinuities of Fig. 3.

### III. The new approach

The method proposed in this paper uses fuzzy logic to perform Quantitative Severity Assessment and also Quantitative Risk Assessment of events. The outputs are numerical values that belong to a scale that varies from 0 to 100. All events and risk models are described by fuzzy sets composed by fuzzy variables, fuzzy terms and fuzzy rules.

#### A. Quantitative Severity Assessment

The construction of a fuzzy set is basically a simple three steps process: Step 1 - identify the input and output variables; Step 2 - define the terms and membership functions of each variable; Step 3 - define the rules of inference. In all of these steps, it’s very important to use the knowledge of the aviation specialists, so that the fuzzy set contains relevant information about the event that it represents.

For the GPWS event, the creation of a fuzzy set is a very simple task because most of the necessary information has already been revealed. The input variables are RA and SR, as shown in Fig. 1(b). The output variable is called Severity and is common to all events. For the step 2, one can define the terms for each variable according to figures 4, 5 and 6.

For the step 3, one can use the qualitative analysis described in Fig. 2 and translate every cell into a rule of inference, e.g.:

- If RA is Very Low and SR is Very High than Severity is Catastrophic
- If RA is Low and SR is High than Severity is Hazardous
- If RA is Low and SR is Medium than Severity is Major

The surface generated by the fuzzy set that represents the Quantitative Severity Assessment of the event GPWS is shown in Fig. 7.

![Fig. 7: Quantitative Severity Assessment of GPWS (Fuzzy Logic approach)](image-url)
B. Quantitative Risk Assessment

When the aviation specialists analyze the occurrence of several events of the same flight, they usually give more importance to the events that represent more danger than to the others. This implies that there is a Partial Risk Factor (PRF) associated with each event, and a Global Risk Factor (GRF) that represents the overall risk. Therefore, the new risk assessment method proposed in this paper relies in three different models:

- GRF model
- PRF model
- Importance model

C. GRF model

The GRF model calculates the GRF of a group of events that occur in the same flight, considering the PRF and importance coefficient K of each event.

In Qualitative Risk Assessment, the aviation specialists tend to analyze the most dangerous events first and then move on to the less dangerous events. The GRF model here proposed is an iterative model that computes only one event per iteration, i.e., the event that corresponds to the highest PRF, as described in (1) and (2).

The first iteration is given by (1):

\[
\begin{align*}
\Phi_1 & = \{PRF_1, \ PRF_2, \ldots \ PRF_n\} \\
GRF_1 & = \max(\Phi_1) \\
K_1 & = 100%
\end{align*}
\]

(1)

All other iterations are given by (2):

\[
\begin{align*}
\Phi_i & = \Phi_{i-1} - \max(\Phi_{i-1}) \\
GRF_i & = GRF_{i-1} + K_i \times \max(\Phi_i) \\
K_i & = k\% \\
i & = 2, 3, \ldots, n
\end{align*}
\]

(2)

The \(\Phi_i\) set is composed by the PRF of the events that have not been yet added to the GRF, and therefore, has to be redefined in each iteration.

The \(PRF_i\) parameters are calculated by the PRF model and the \(K_i\) coefficients are given by the Importance model.

D. PRF model

The PRF model here proposed calculates the risk associated with a single event, and therefore, is based on the risk model used in [17], [18] and [25].

The construction of a fuzzy set that represents the PRF model is a very similar process to the construction of the GPWS fuzzy set. The input variables are the Probability of Occurrence and Severity. The output variable for this model is called Coefficient and relates to the PRF of an event. The terms of each variable and the qualitative analysis that leads to the inference rules are described in Table III. The surface generated by the fuzzy set that represents the PRF model is visible in Fig. 8.

E. Importance model

Sometimes in risk assessment, there are events considered to be more important than others because they represent a more dangerous situation. The Importance model here described assigns an importance coefficient K to each event according to two criteria:

- GRF value
- PRF ratio

**GRF value** – This criterion is based on the assumption that there is not much sense in giving great importance to events in the situations where the GRF is already too high. In fact, the importance given to an event in iteration \(i\) should depend on the value of the GRF already reached in the iteration \(i-1\) of the GRF model. Therefore, this criterion considers that the importance of the events should diminish as the GRF gets higher.

**PRF ratio** – The circumstances concerning the events are never the same. They change from flight to flight. That’s the reason why the importance of an event should depend on the context in which the event occurs.

This criterion defines a parameter \(Q\) that measures the correlation between events of the same flight. \(Q\) is given by the
ratio between the PRF of each event and the highest PRF of the group of events.

An event with high Q means that it should be considered as a high importance event and vice-versa.

The GRF value and PRF ratio criteria are used as input variables in the fuzzy set that represents the Importance model. The output variable is called Coefficient and corresponds to the importance coefficient K used in the GRF model.

The surface generated by the Importance model fuzzy set is in Fig. 9, and it shows that an event gets less importance as the PRF ratio gets smaller and also as the GRF value gets higher, according to the criteria considered.

IV. CALC RISK SOFTWARE

A. Creating fuzzy sets

The CalcRisk software was created in the context of this paper and was designed to perform Severity and Risk assessment of events. Because all events are described by fuzzy sets, CalcRisk has a tool that allows users to easily create fuzzy sets. Fig. 10 shows the first step of the creation process of the fuzzy set that represents the event called Example; witch is composed by the variables: Variable 1, Variable 2 and Severity.

The user can specify the name, units and limit values for each variable. It is also possible to create a multi layer fuzzy set by choosing the Parent option. A multi layer fuzzy set is composed by variables that are themselves fuzzy sets and is suitable to describe more complex events.

Fig 9: Importance model

Fig 10: Creating fuzzy sets interface - Variables

Fig 11: Creating fuzzy sets interface - Terms

Fig 12: Creating fuzzy sets interface – Rules of inference

Fig 13: Fuzzy sets 3D surface viewer
Fig. 12 shows how a user can create the rules of inference of the fuzzy set. The user specifies the type of connection and the weight of each rule. There is also an option that allows the user to view the 3D surface resultant from the current definition of variables, terms, membership functions and rules of inference, as shown in Fig. 13 for the Example event.

B. Main Interface

The main interface allows the user to create several reports simultaneously and is divided in the following nine different areas, as shown in Fig. 14:

1 – Report tools  
2 – Event tools  
3 – Fast access tools  
4 – Events panel  
5 – Severity panel  
6 – Risk Panel  
7 – Current PFR model  
8 – Current Importance model  
9 – GRF value

C. Severity assessment

The Severity assessment of any event is the outcome of the defuzzification process of the fuzzy set that represents an event, as shown in Fig. 15. In Fig. 15 each column represents a variable of the fuzzy set and each row represents a rule of inference. The defuzzification method implemented in CalcRisk is the centroid method.

D. Risk assessment

The Risk assessment is accomplished by applying the assessment methods presented previously in this paper. An example of risk assessment for an occurrence of four events is shown in Fig. 16. Because of data protection issues, the severities and likelihoods here presented are merely fictional and serve only for demonstrating purposes.

In the CalcRisk application, the user can select different PRF models and also different Importance models for each specific analysis. The example of Fig. 16 uses the PRF model called ICAO and the Coefficients 1 Importance model.

The Weather Radar – Windshear Alert event has the highest PRF (38.51 %) and therefore, gets the highest importance coefficient (100 %). The resulting GRF is 61.58 %.

V. Conclusion

The use of fuzzy logic contributes to an easier understanding and a much natural way of expressing the aviation events and risk concepts.

The fuzzy logic version of the Quantitative Severity Assessment method has managed to transform the discontinuities of the traditional method (Fig. 3), into a continuous and smooth surface (Fig. 7). This is a great improvement because it allows greater precision in assessments and avoids flat classes.

Most of the existent risk assessment tools specify single values or ranges of values for the several risk related concepts. The model presented in this paper doesn’t specify values of any kind. Instead, this model only specifies criteria that compute dynamic risk assessment, according to the context of each event.

The CalcRisk software is a powerful tool that allows any user to easily create fuzzy sets that represent events and perform Severity and Risk assessment.

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REFERENCES