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State Aviation Risk Assessment Level Determination Using Hierarchical Fuzzy Inference System Based on Cognitive Maps

Alvimar de Lucena Costa Junior [1,*], Mischel Carmen Neyra Belderrain [2], Moacyr Machado Cardoso Junior [3]

[1] Gestão e Apoio à Decisão / Ciências Fundamentais / Instituto Tecnológico de Aeronáutica
Praça Marechal Eduardo Gomes, 50 Vila das Acácias, 12228-900 São José dos Campos/SP – Brasil
alvimar.lucena@gmail.com
[2] Gestão e Apoio à Decisão / Ciências Fundamentais / Instituto Tecnológico de Aeronáutica
Praça Marechal Eduardo Gomes, 50 Vila das Acácias, 12228-900 São José dos Campos/SP – Brasil
carmen@ita.br
[3] CNPJ: 64.037.492/0001-72 / ITA/FCMF / Instituto Tecnológico de Aeronáutica / Fundação Casimiro Montenegro Filho
Praça Marechal Eduardo Gomes, 50 Vila das Acácias, 12228-900 São José dos Campos/SP – Brasil
moacyr@ita.br
*Corresponding Author: Alvimar de Lucena Costa Junior, Email: alvimar.lucena@gmail.com

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Abstract

During 2018, ICAO (International Civil Aviation Organization, a specialized UN organization) made available the results of its USOAP (Universal Safety Oversight Audit Program): the ratio of compliance for each ICAO member State to 1047 aviation safety-related protocol questions, divided into eight audit areas. Numbers itself has little meaning, even for aviation personnel. Using Cognitive Mapping (CogMap), a Problem Structuring Method tool, this paper develops a framework to extract and organize information from aviation specialists, allowing define Risk Assessment Level for each State, and for each Aviation Safety Branch defined. Using Fuzzy Inference Systems (FIS), helpful supporting decision making, Big Data available from ICAO is converted to Risk Levels for each State and audit area, what may be used to make informed better Safety decisions on the World Aviation Market. Up to the moment, there's no evidence on the literature of using CogMap to establish a FIS.

Keywords

Hierarchical Fuzzy Inference System, Cognitive Mapping, Risk Assessment, Problem Structuring Methods, Civil Aviation

1. Introduction

In 1999, the International Civil Aviation Organization (ICAO, a specialized United Nations organization) launched the Universal Safety Oversight Program (USOAP) [4]. The program audits all ICAO States for conformity with the Standards and Recommended Procedures (SARP) described on Chicago's International Civil Aviation Convention and correlated documents. After 20 years of USOAP development, the Program is now focused on a Continuous Monitoring Approach (CMA) and has made public the numeric results of its Audits, the compliance ratio of all 1047 aviation safety Protocol Questions (PQ) on all 185 ICAO member States. [3]

The PQ table has the information divided into eight different Aviation Safety Audit Areas. The table includes the last audit result for every State, using results from dated 2005 up to 2018, and every number is the compliance ratio between the number of accomplished satisfactorily PQ divided by the number of State applicable PQ, which means, not all States has answered all 1047 PQ.

As a cold number, the results mean little, once nobody could say if 70% is a bad, a very bad, a good or a very good number for a State. Comparing with other countries, results could provide a better understanding, but the lack of a pondered weight for each Question or Audit Area or a definition of what may be considered "good" or "bad" make every PQ have the same value for the final average result.

The problem proposed is how to organize this data based on aviation experts' knowledge, in order to these numbers become valid information for decision and allowing a Decision Maker to be able to ascertain which States are High Risk, and how the risk is presented.

The objective of this paper is to describe a method to solve this problem, by eliciting information from aviation experts about USOAP results using Cognitive Mapping, a PSM Tool, and Hierarchical Fuzzy Inference System, so that each crisp grade available may be converted on a linguistic Risk Assessment level and deliver more useful knowledge organized in a hierarchical format.

During the research for this work, the author search for terms "Hierarchical Fuzzy Inference System", "Hierarchical Fuzzy Control" and "Fuzzy Control" allied with "Problem Structuring Methods", "Cognitive Maps" and "Multicriteria Decision Analysis", on main academic papers repository and search-engines, like Google Scholar, Elsevier and Science Direct. Many works on the fusion of Fuzzy Logic and Multicriteria have been found, mainly related to Fuzzy AHP (Analytic Hierarchy Process) [5] and Fuzzy TOPSIS [12]. These types of fusion have applications on ranking options and are better to handle a small number of options. On the other hand, for the USOAP case, the main objective was to classify by Risk

Level 185 States, using data from eight “sensors” (audit areas).

Another type of work found was Fuzzy Cognitive Maps (FCM) [8]. FCMs are a kind of Cognitive Map that takes the initial concept [2] and transforms the standard + and – connections between concepts to fuzzy connections like “increases a little” or “decreases a lot”, adding more meaning to classical Cognitive Maps. Efe [16] showed an application of FCMs on Hazard Evaluation.

Neither way of connecting the Fuzzy Logic to Multicriteria or PSM were identified to help accomplish this paper’s objective.

It is important to notice that USOAP Audit Areas Grades were used as a mirror to the effective situation of the Aviation Safety of the State, but that’s not completely accurate.

ICAO auditors focus on how the State’s Civil Aviation Authorities deal with ICAO Safety requirements. That way, the USOAP grades will better mirror the actual situation of Aviation Safety on the same ratio that the Authority accomplishes success on the surveillance and enforcement of its legislation.

Although the USOAP grades are a fair estimation of the Aviation Safety situation on the State, it should be studied under the light that these numbers are only proxies to the actual situation of Air Operators, Navigation Service Providers, and Airport Operators.

The paper presents five sections. The present first section defines the scenario and the objective of the work done. The second section presents a summary of the used theory and the third section presents the developed method. Forth section brings the results of the described method on USOAP results. Finally, the fifth section delivers the conclusion and post-work suggestions.

2. Theory

2.1. Fuzzy Logic

Fuzzy logic is a way of interpreting the world in imprecise terms and corresponds with precise action. This logic tries to emulate the way the human brain works, dealing with uncertainties, vagueness, and judgments. It can simultaneously handle numerical data and linguistic knowledge and is a precise problem-solving methodology.

The concept of Fuzzy Sets was firstly introduced on “Fuzzy Sets” [15] and aimed to allow computers to determine the distinctions among data with shades of gray, like the process of human reasoning.

Using the concept of Fuzzy Logic, Fuzzy Inference System (FIS) was first referred to as “Linguistic Synthesis with Fuzzy Logic” [9]. It’s a process that allows outputs to be based on given inputs using fuzzy logic. The crisp, precise inputs are first fuzzified, which means, turned from a precise number to a fuzzy class, or truth values, linguistic variables. The fuzzification process is based on a membership function defined for each input.

Then, these linguistic variables are examined under a set of rules that will convert these inputs on output linguistic variables.

To complete the process, output membership functions are used to defuzzify the variable, returning a crisp value as output in the end.

Fuzzy Inference Systems (FIS) are used mainly on control, as the Mamdani example itself was a fuzzy control for a steam engine. But they have been successfully applied in fields such as automatic control, data classification, decision analysis, expert systems, and computer vision [6].

Under the concept of the FIS process, all input linguistic variables are subjected to the same set of rules. When the number of sensors and inputs come to be very large, the organization of those rules tends to be overwhelming. The number of rules in a standard fuzzy controller increases exponentially with the number of variables involved [14].

The hierarchical fuzzy system, proposed by Raju et al. [10], provides a way to deal with this problem, hierarchically connecting low dimensional fuzzy systems.

2.2. Problem Structuring Methods: Cognitive Maps

To reach a useful hierarchical organization of the presented problem, this paper proposes the use of a Problem Structuring Method (PSM) tool. The study of PSMs begun during the ’80s, as a new issue discussed on some Operational Research texts. The term PSM was only created in 1989. [11]

PSMs are characterized by Systems Thinking, and for using primary qualitative models [11]. Besides that, when needed, PSM can handle many criteria, focusing not on specific process optimization of, but, otherwise, on the complete understanding of a situation or a problem.

PSM has many defined and classical methods, from those we may point out three as the main ones: Strategic Choice Approach (SCA), Soft Systems Methodology (SSM), and Strategic Options Development and Analysis (SODA) [1][13]. Each of these methods employs several specific tools, by what they are most remembered. For SSM, the Rich Picture. For SCA, the four Modes. For the SODA, the SODA Map, an instance of Cognitive Maps.

Cognitive Mapping is a technique grounded on Kelly’s theory of personal constructs [7], which has been developed over a period and through its application has demonstrated its use for Operational Researchers working on a variety of different tasks. [1]

It is used to structure, analyze, and make sense of accounts of problems.

Cognitive Maps (CogMaps) help also to structure messy or complex situations, help interviews by increasing understanding and generating agendas, being able to handle large amounts of qualitative data from talks and documents.

Drawing CogMaps help not only understanding problems by its structure but during its process, allows representing messy situations on a hierarchical, groupable format. Also, CogMaps allow new insights into the problem, for the visual approach it gives to the elicited interviewee. [2]

3. Method

Figure 1 shows a summary scheme for the method.

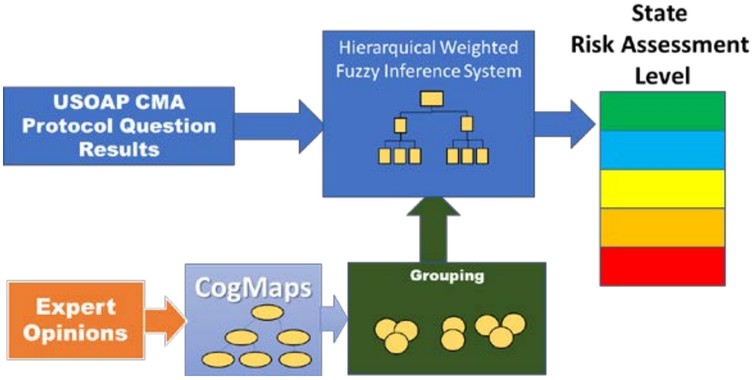

Figure 1. Method Summary Scheme

The USOAP Results table comprises all PQ Results achieved by the 185 ICAO member States for all eight areas of Audit: Flight Operations (OPS); Airworthiness (AIR); Aerodromes (AGA); Personnel Licenses (PEL); Legislation (LEG); Organization (ORG); Aircraft Accident and Incident Investigation (AIG); Air Navigation Services (ANS). [3]

In order to arrange these eight areas on groups or classes, twelve aviation experts were consulted. They were interviewed under the Cognitive Map Technique, using the guide question: “Which elements should compose a State Operation Risk Index?”. Among these experts, the author also took part, using his fifteen years of work experience on a Civil Aviation Authority.

In that phase, the Experts were not confronted with the eight audit areas. These areas were supposed to be raised naturally during discussions, which would diminish interviewer influence and biases.

During the interview, a CogMap was drawn, so the interviewed could check and validate if the connections and levels for the maps were according to what he understands as correct to answer the question.

Every new element inserted on the map was challenged by other decomposition question: “Which elements should we consider getting to this one?”

Three different CogMaps were drawn, all aggregated as one using similarities on opinions and constructs of ideas. One example of an initial CogMap is shown in Figure 2. Figure 3 presents the aggregated CogMap.

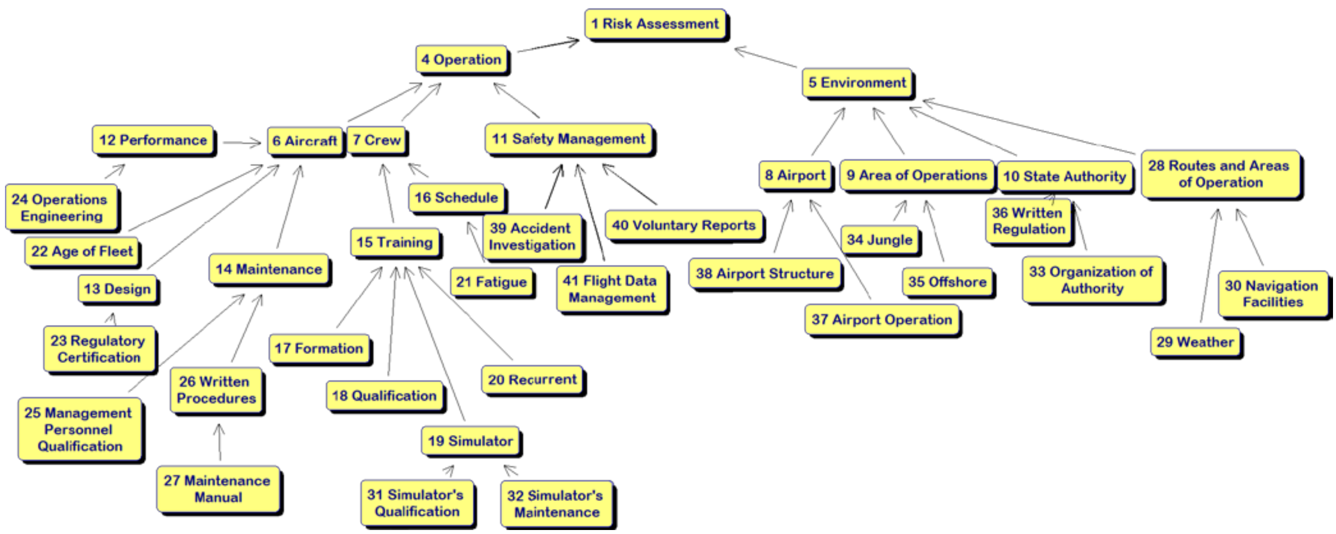

Figure 2 – Author’s and Operations Experts Map

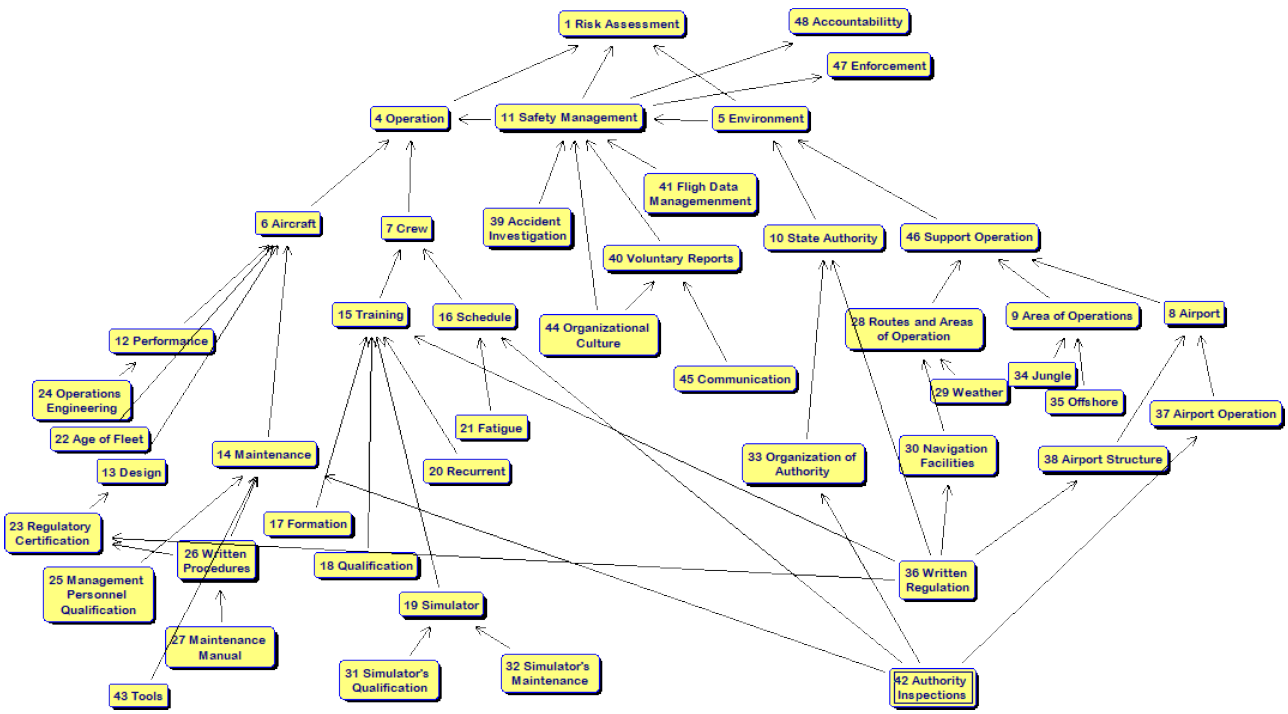

Figure 3 - Aggregated Map

Based on these maps, using a CogMap cluster analysis, three large areas were identified: Operations, Safety Management, and Aviation Environment; under Aviation Environment, two other concentration areas: State Authority and Operation Support. Under these concentration areas, all audit areas can be found, as can be seen in Figure 4, colored by each area to ease understanding.

Each of the constructs that are part of the Aggregated CogMap is painted with the corresponding color of the audit area.

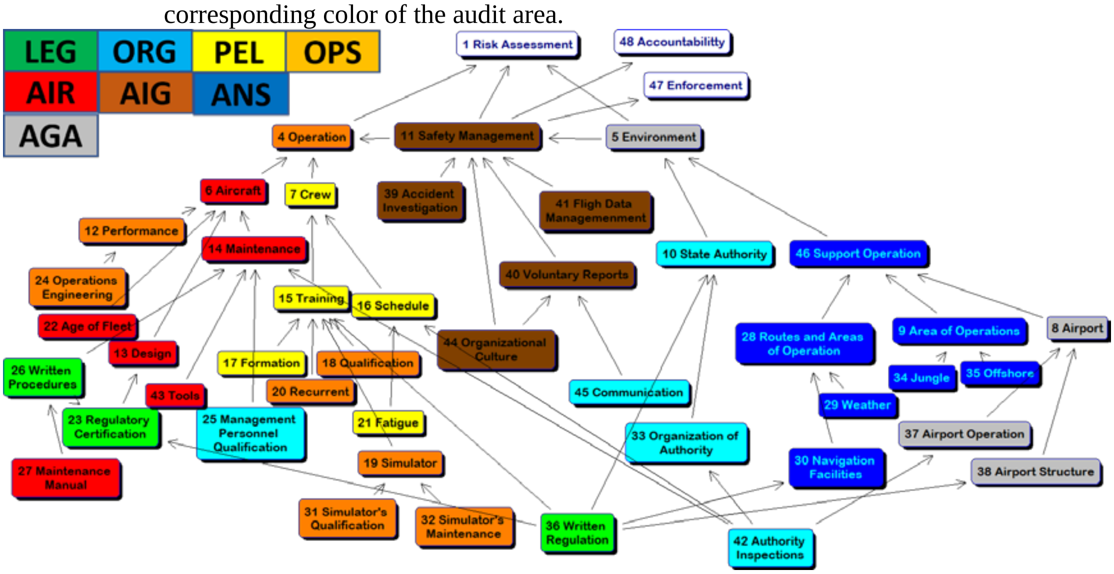

Figure 4 – Aggregated CogMap colored to USOAP Audit Areas

Based on this study, the Hierarchy of Figure 5 was built.

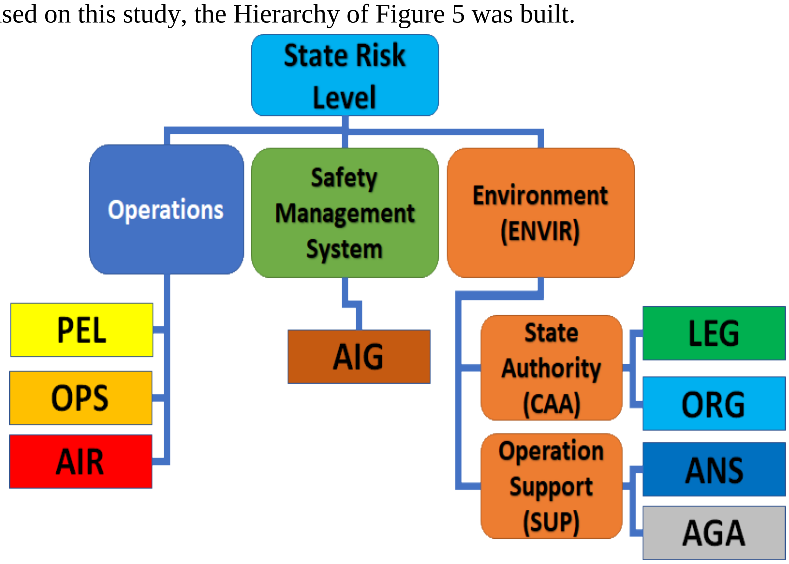

Figure 5 – Hierarchical Organization of USOAP Audit Areas

This structure enabled the application of a Hierarchical Fuzzy Inference System, and the linguistic variables were defined also based on the opinion of aviation experts.

An interesting side-product of the hierarchization process was that every branch defined during the CogMap discussion phase has its own Risk Index and Risk Level defined for each ICAO member State.

The Operations Branch (OPE) includes all information belonging to how operators are inspected to conduct their flights.

The Civil Aviation Authority (CAA) Branch takes care of all information related to how the State's CAA is organized and how it can enforce its regulations.

The Operation Supporting Branch (SUP) includes both areas that cover everything that an operator needs to operate a flight.

The Environment Branch (ENV) assesses and combines both CAA and Supporting risk indexes.

The crisp number used to quantify the Risk level or each state on each area was the percentage of protocol's compliance for each audit area, to what we refer here as Index. That way, a higher Index for a specific audit area corresponds to a lower risk level.

The final combined Index, State Risk Index (STA), combines all indexes obtained before, allowing classify each State using all information available. The hierarchic nature of this framework is also a way to give different weights to each Audit Area. One example of weighting is the position where the experts put the construct relative to the AIG audit area (Safety Systems and Accident Investigation). Risk Index related to the AIG area itself has the same strength of the Operations (OPE – the result of three audit areas) and Environment (ENV – the result of four audit areas).

All audit areas Indexes were then fuzzified using triangular membership functions, and all output branches were defuzzified with gaussian membership functions. MATLAB toolbox Fuzzy was used for solving the Inference System.

For the Operations Branch, three-level memberships were defined (HIGH, MEDIUM, LOW Risk), as well as for the AIG audit area.

For the CAA and SUP branches, the membership functions were two-level ones (HIGH, LOW), as the sample's distribution was already very concentrated.

Membership functions (MF) for the linguistic variables for each Risk level were defined with no intersection. That means that a crisp value corresponds to a unique linguistic level, with no gradation for any other.

As verified by the author by experiment, the behavior of no intersection MFs produces a more distinctive result for output, defining precisely which points of a sample are on each linguistic variable level. That way, all sets of MFs were defined with no intersection.

For the three-level branches, a total of 27 rules were defined for each FIS. For level two, two elements branches, four rules were defined.

The determination of each set of inference rules was discussed on the same group of experts, using mainly classical colored Risk Matrices for illustration and support.

4. Results

The most relevant information for a Safety Evaluation is which are the High-Risk States for each area, so Decision Makers could use the information for better and Safer outcomes.

It is important to mention that the objective of this paper is to present a method to classify States for its Risk Levels, but there would be of no use to uncover which States are classified as High Risk, once the same method could be applied using other aviation experts and other States could be appointed as High Risk.

The Fuzzy Inference System for the Operations Branch is shown in Figure 6.

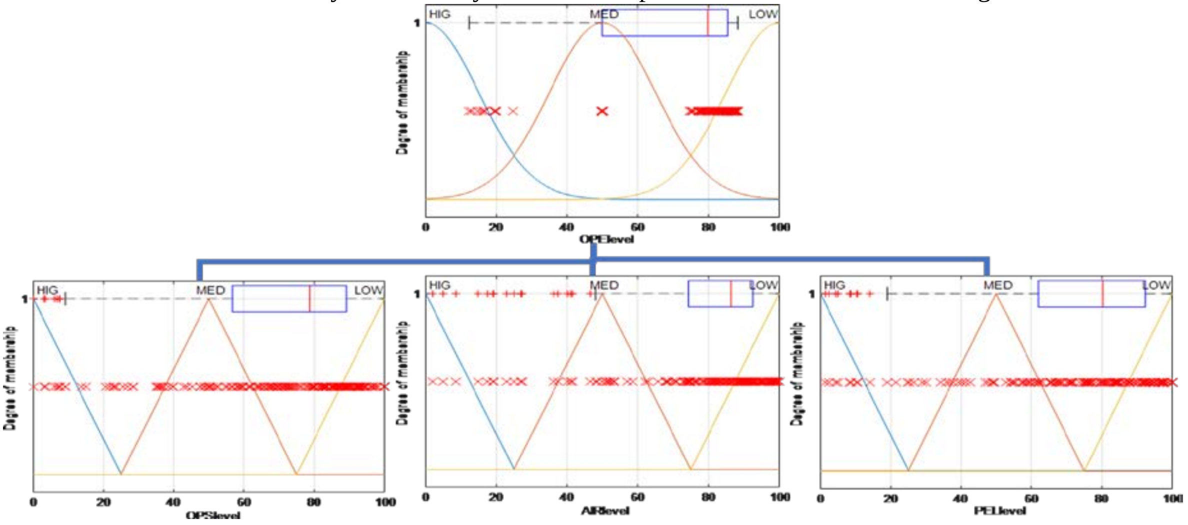

Figure 6 – Membership functions for Operations Branch Fuzzy Inference System

Observation: 1) red "X" – Crisp USOAP grades for all States

2) Each membership function graph includes a boxplot for the grade distribution

3) red "X" on OPE level graph are the Crisp defuzzified Risk Levels for each ICAO member State

4) The same observation applies for all other FIS figures

The FIS for the Operations Branch shows a concentration of defuzzified Risk Indexes between HIGH and LOW. A total of twelve States may be classified as High Risk in Operations, and the best Index result between these is 24,70%, which means, an equivalent adherence to protocol questions of around one quarter. Also, the fraction of twelve High-Risk States among 185 States examined is a 6,48% proportion of States to be more cared for.

A Decision Maker could use this result for the Operations area to infer that contract an Air Operator from one of these High-Risk Level countries would have a higher risk of accident than from other Medium or Lower-Risk Level States. Problems related to training pilots and mechanicals, to keep aircraft safe and to operate safely would be more common in these States.

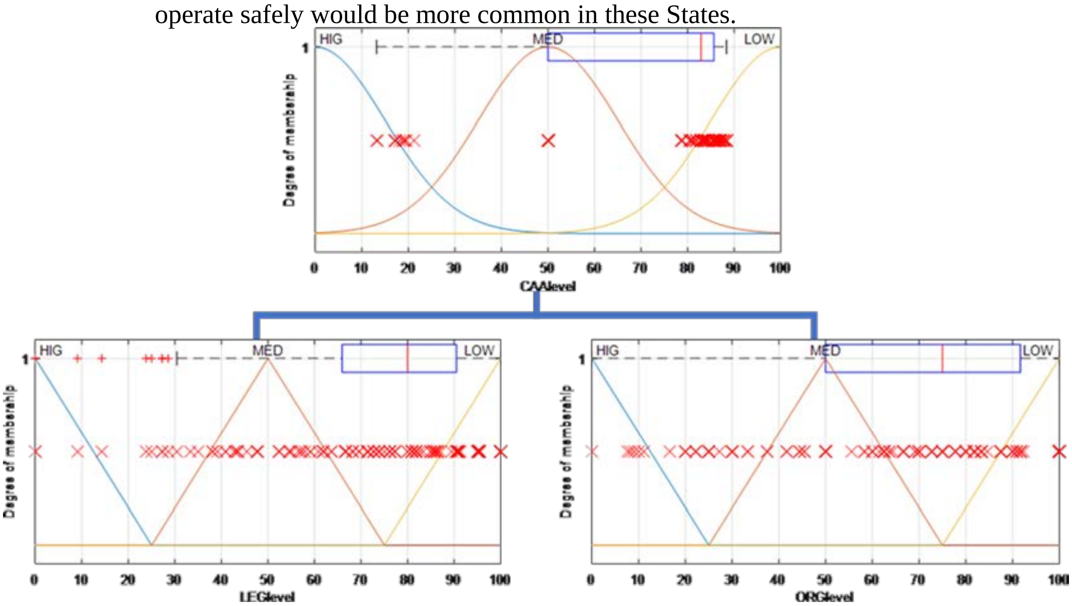

Figure 7 – Membership functions for CAA Branch

The same behavior of concentration identified on the Operations Branch has been seen on CAA Branch, as may be seen in Figure 7.

This way, on the CAA Branch, fourteen States (7,56% of All States) were classified as having High Risk in their Civil Aviation Authority Structures. Between these States, the best Risk Index calculated was 21,22%.

A CAA High-Risk Level State would have problems related to the legitimacy of the Civil Aviation Authority and its inspectors. Also, these organizations would have weaker enforcement actions and would be less able to make their regulated aviation providers comply with safety requirements.

For the SUP Branch, Figure 8 shows that 34 States (18,38%) were classified as having High Risk on their Supporting Structures, which included Navigation

Services and Aerodromes. Between these States, the best Risk Index calculated was 25,55%.

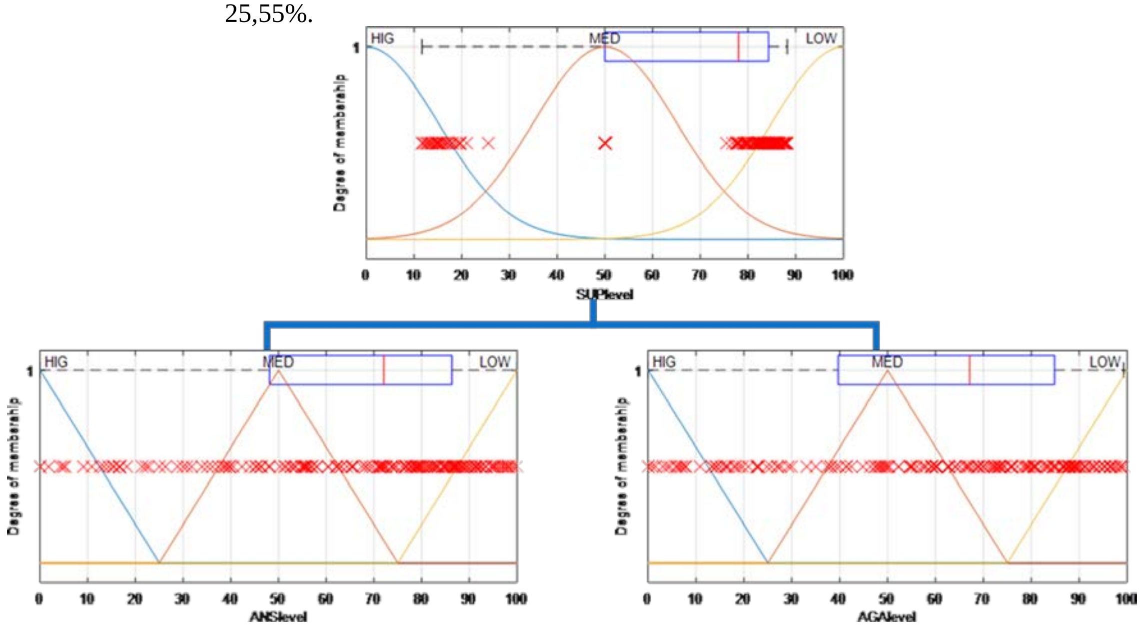

Figure 8 – membership functions for SUP Branch

A SUP High-Risk State would be one where Airports, runways, and Air Traffic Control could have problems with its construction, maintenance, and operation, once safety requirements for the safe operation would not be enforced or well established. For example, Air Traffic Controllers would not be trained on the same standards that lower-risk countries and runways would be built without taking into care the most adequate resistance and brake capabilities.

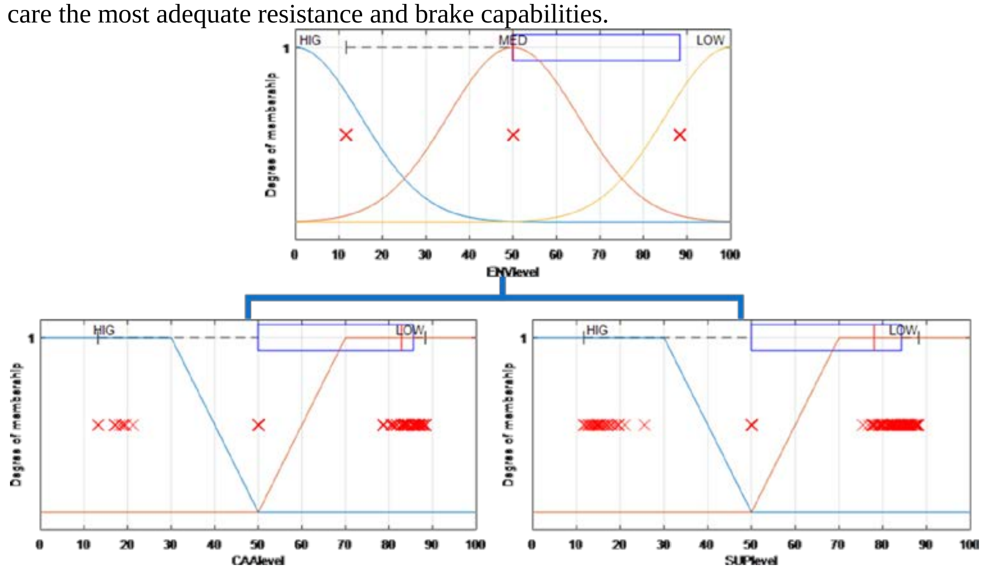

Figure 9 - membership functions for ENV super Branch

For the ENV Branch, twelve States (6,48% of States) were classified as having High Risk on their Environment for Safety Aviation Organizations, as may be checked in Figure 10. Between these States, the best equivalent adherence to protocol questions (Risk Index) was 11,65%. One point to highlight on the ENV Branch is that the two-level FIS translated all crisp indexes to the same three values, once all High and Low index levels for CAA and SUP were concentrated on the unity value of membership, disabling the distinguished indexes that existed before using the FIS.

The ENV Branch Risk results bring a balanced summary of all conditions for aviation operations on a State, from an Air Operator's perspective. The ENV Risk level would guide, for example, a foreign Air Operator to choose the best place to install an Operations Base or a good place to initiate an expansion for new routes.

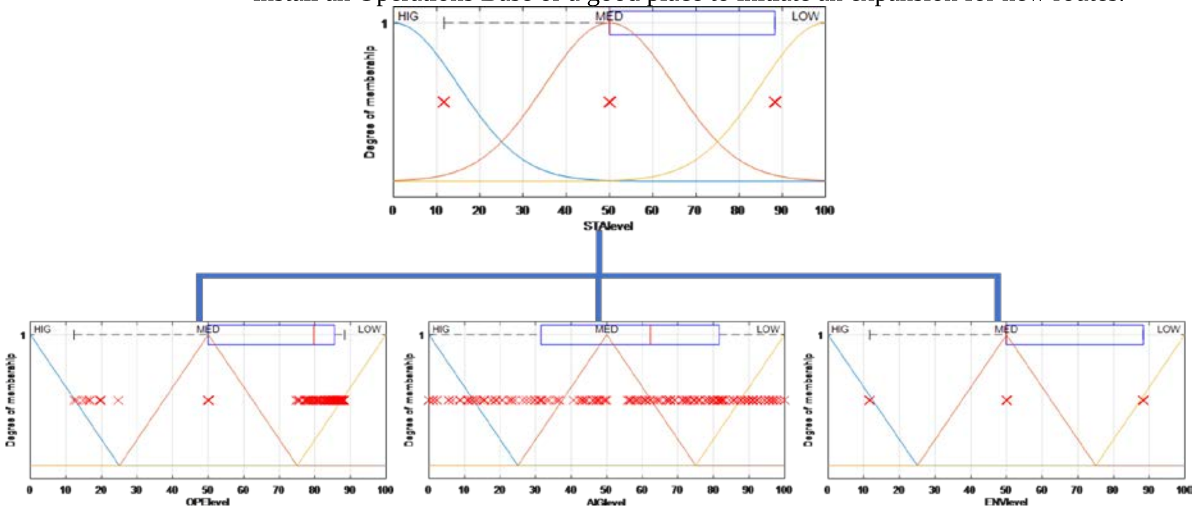

Figure 10 - membership functions for State Risk Branch

Finally, for the State Risk Assessment System, fifteen States (8,1% of States) were classified as having High Risk on their role Aviation System, including their Operations, Safety Management, and Accident Investigation and Environment for Safety Aviation Organizations. Between these States, the best Risk Index calculated was 24,54%.

The STA Risk Level summarizes all information related to a State's safety aviation system, allowing a Decision Maker to assess, in overall, if this aspect contributes, or not, to build a new Vacations Resort, or to establish a new branch for his corporation, for example.

5. Conclusion

The presented multimethodological process was able to combine the qualities of a PSM tool to a mathematical resource for scenarios with a lack of information.

During the CogMap process, the author was able to elicit aviation experts to determine a hierarchical organization for the USOAP audit areas.

One important result of this CogMap approach is that it allowed determining branches of audit areas and respective Risk Index and Level that could be analyzed by itself, which permits a wider consideration of a State's Aviation Safety situation. Another strong point of the method is the hierarchical organization that permits attribute different weights to each audit area, giving higher or lower importance according to the group it belongs to.

The Hierarchical Fuzzy Inference System process was able to separate all States on distinctive groups, using studied rules of inference, allowing precise identification of the High-Risk States for each audit area and each head or branch of audit areas. Also, the rules applied were able to select a small number of States that should be more carefully followed, which may make it easier to prioritize efforts. The resultant groups of High-Risk States are of high value for many industry areas, like insurance brokers, charter operators, and tourism agencies.

One recommended future work would be to establish correspondent Protocol Questions to be used directly on Air Operators, Air Navigation Service Providers, Airport Operators, and other actors on Aviation Safety on each country, to establish better risk indexes referring to each Civil Aviation Services Provider and each audit area.

Having these new results in hand, it would be possible to re-run the same method, using more aviation experts, and get to a wider hierarchical system, that may handle even more information to turn to more useful knowledge.

Acknowledgments

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Conflicts of Interest

The authors declare that the submitted work was carried out in the absence of any personal, professional, or financial relationships that could potentially be construed as a conflict of interest.

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