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Method for evaluation of the influence of LPV-200 procedures usage on the probability of CFIT

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ABSTRACT: Navigational equipment available at many airports, especially the small ones, does not let to maintain precision approach landing procedures. Installing more sophisticated equipment often has no economic justification. Because of this, airports usage is reduced. The main goal of this paper was to propose to use LPV-200 procedures at this kind of airports, which allow for approach that looks like ILS category I approach, but only lightning system equipment is needed for the operations. However, this concept raises a practical question – how safe this solution is? It should be minded, that using LPV-200 procedures will allow the aircraft to descent to the height lower than usual, without visual contact with the surface. So a research problem exists – if this kind of activity won't increase CFIT (Controlled Flight Into Terrain) accident probability. In this paper we propose to use fuzzy sets theory, specifically fuzzy inference systems, for probability of CFIT (PoC) calculation. For this aim a hierarchical fuzzy model concept was made, a local models structure was proposed and one of them was studied in more details and implemented. As a final result, a strong tool was obtained, which after full implementation will allow to determine PoC. Initial analysis shows, that using LPV-200 procedures is not only not increasing PoC but also may decrease it. However further research is needed in this area, particularly further verification and supplementation of the expert's knowledge, which is a basis for building the proposed fuzzy inference systems.

1 INTRODUCTION

Airports areas are being characterized by the congestion of air traffic. Approach procedures which are being maintained are complicated, there is a big workload, both of pilots and air traffic controllers. All this causes that approach and landing flight phases are the most crucial due to the air traffic safety. Most of the accidents occurrences in those areas are categorized as CFIT (Controlled Flight Into Terrain), in which an airworthy aircraft, under pilot control, is unintentionally flown into the ground. Results of these accidents are mostly fatal with many casualties. Landing approach procedure is mostly supported by ILS (Instrument Landing System) of determined category, which makes it possible to continue approach without visual contact with the ground to a specified height. However, a lot of airports, especially the small ones, cannot afford ILS installation. This rises a problem, how to develop procedures which allow ILS-like approach with a ground infrastructure limited to runway lightning. Simultaneously there is a question if this is possible without increasing the probability of CFIT (PoC). The problem of calculating PoC is one of the most important in case of introduction of any novelty in airport area traffic management (Ken, 2013).

In this paper a study on implementation of LPV-200 (Localizer Performance with Vertical guidance) procedures is being presented, which determined a kind of completely new attitude to the approach and landing procedures (Dautermann et al., 2015). It relates especially to the countries in which the program of APV (Approach Procedures with Vertical guidance) implementation did not have the desired effect (Fellner et al., 2012). An analysis of the present solutions due to CFIT accidents statistics was carried out. Based on the analysis results, practical realization of the LPV-200 procedure for specified airport can be proposed. At the same time a method for evaluation of the CFIT probability was proposed. This evaluation is really difficult, because there are many factors affected on it, some of them are subjective and dependent of human factor. These factors had been determined, inference rules had been defined, definition of output variable had been formulated – an original logarithmic scale of fuzzy prob-ability. Based on the model built, experiments were conducted to find how the probability of CFIT will change after implementation of LPV-200 procedures.

In case of finding that implementation of LPV-200 procedures have not increased the probability of CFIT (or even decreased), application of the developed solutions will allow to achieve many goals. It would be possible to significantly decrease airport infrastructure costs due to no need of new ILS equipment installing. It would be possible to reduce a pilot workload because approach and landing procedures will be more readable and uniform. As well for the air traffic control service it will be a great facilitation, because of possibility to achieve higher flexibility of the airspace.

2 AIR TRAFFIC IN TERMINAL AREAS

Due to acceleration of economic and social activities as well as globalization, air traffic services are indispensable as part of the growth of the air transport sector. The air traffic systems in airport areas are becoming increasingly important as the foundation of aviation services. That is why increasing safety during approach and landing flight phases is a major prerequisite in establishing a future air transport architecture. Today's huge and fast air traffic development brings about some new problems.

Most of modern airports are located in or near cities where areas with restrictions are – habitat zones, mountains, oceans – these are restrictions on setting departure and approach routes, radio waves for ground-based communication, navigation and surveillance. More flexible use of airspace is desired and safety needs to be increased.

As existing en-route, arrival and departure routes are established based on ground Navigation Aids (NAVAIDS), the routes are not established flexibly and efficiently due to the locations of these ground NAVAIDS, their accuracy and limited radio coverage. In particular, sometimes it is impossible to establish an efficient route or precision approach for a runway due to land features or the influence of residential areas near the airport. Although performance-based navigation (PBN) such as RNAV has been introduced, operation that gives greater importance to aircraft capability such as high-precision RNAV enabling curved approaches and more strict assignment of required time of arrival and satellite based navigation will become important (ICAO, 2008).

3 SAFFETY OF AIRPORT AREA OPERATIONS

Both the aircraft and the airspace system are becoming busier and more complex, flight deck systems and procedures are becoming more complex. Solutions to safety problems, operational problems, and communications problems are traditionally addressed by incrementally adding new procedures or extending the functionality of existing procedures.

Due to the changes which have taken place since the conclusion of the Chicago Convention, including the expansion of the international civil aviation community, the liberalization of the aviation industry, the introduction of new technology, and the existing as well as the new and emerging threats by terrorism, aviation safety has already become a global issue and could not be adequately and effectively addressed within the limits of national boundaries.

Most of the accidents occur during the approach and landing phases of the flight which is the most sensitive phase of the flight and account almost half of the fatalities worldwide. In contrast, the duration of the approach and landing phases typically is 16 percent of the total flight time. It is essential to have qualified personnel whose knowledge of the rules of the air is kept up to date for purposes of ensuring the safety of aviation, this alone is by no means sufficient. They must also be equipped with reliable machines and tools (Skorupski, 2015a). Accordingly, aircraft, defined as "any machine that can derive support in the atmosphere from the reactions of the air other than the reactions of the air against the earth's surface", must be airworthy. Historical scientific observations have shown that accidents are normally the result of contributing factors across multiple aspects of the aviation system. As a natural consequence of the service that aviation transport sector provide, airlines are exposed to operational risks which must be continuously monitored and mitigated. International Air Transport Association (IATA), through its Global Aviation Data Management (GADM) program, has identified three major areas of concern:

- Loss of Control In-flight,
- Runway Safety,
- Controlled Flight Into Terrain.

CFIT refers to accidents in which there was In-flight collision with terrain, water, or obstacle without indication of loss of control. The critical distinction in these types of accidents is the fact that the aircraft is flyable and under the control of the flight crew. There are numerous causal and contributing factors of such events. Typically, aircraft malfunction is not the main cause of CFIT accident; rather the accident's probable and immediate causes are often attributed to flight crew or human error, such as non-compliance with established procedures (SOPs), inadequate flight path management, lack of vertical or horizontal position awareness in relation to terrain, not stabilized approaches, and failure to initiate a go-around when a go-around was necessary. The absence of precision approaches has also been noted as a factor in CFIT accidents.

Although few in number, CFIT accidents are almost always catastrophic, 91 percent of the accidents involve fatalities to passengers or crew. CFIT is the second largest fatal accident category after Loss of Control Inflight (LOC-I) (IATA, 2015a). CFIT accidents were responsible for 14% of fatal accidents analyzed in 2014, however the loss of control inflight occurrence category represented only 2% of all 2014 accidents, this category is of significant concern as it accounts for 29% of all fatal accidents and 31% of all fatalities (the highest by proportion) (IATA, 2015b).

In the period from 2010 to 2014, data from the IATA GADM program shows that 41% of CFIT accidents involved the lack or unavailability of precision approaches. There is a correlation between the lack of ILSs or state-of-the-art approach procedures – such as PBN and CFIT accidents. IATA works collaboratively with industry stakeholders such as ICAO, Air Navigation Service Providers (ANSPs) and airlines to leverage each of the pillars of safety strategy as they relate to PBN implementation.

To reduce the risk of CFIT IATA is continuing its work with states, ANSPs, airlines and international, regional organizations to accelerate the implementation of PBN in accordance with ICAO General Assembly Resolution.

4 SATELLITE-BASED SYSTEMS FOR AIR TRAFFIC SUPPORT

Global Navigation Satellite System (GNSS) as an umbrella term for systems which are used to navigate and determine current position, nowadays became a major source of navigational information which is delivered to the aircraft in every phase of flight. In today's aviation, conventional ground based (ILS, PAR, TACAN, NDB, VOR, etc.) or inertial (INS/GPS) systems have substantially been used as the primary navigation and landing aid for various types of aircraft and operations. Although the conventional systems are highly accurate and some systems, ILS and PAR, can also support precision approach and landing capability up to CAT-3, there are still some drawbacks related with these systems which prompt the users to search for better alternatives.

Navigation technologies with approach and landing systems based on global navigation satellite systems (GNSS) stand as a prominent alternative to the existing systems in terms of usability in all flight phases, providing approaches to airfields which lack navigation aid infrastructure and supporting ease of airfield installation and maintenance. However, due to various types of error sources which affect GNSS based operations, key requirements such as accuracy, integrity, availability and continuity for safety critical aviation applications cannot be fulfilled by standalone GNSS usage. At this point, augmentation systems for satellite navigation, namely the satellite based augmentation system (SBAS) and the ground based augmentation system (GBAS), present promising, state of the art and cost effective solutions, meeting the performance requirements for different phases of flight from take-off to landing by aiding aircraft navigation subsystems to minimize the amount of error from standalone GNSS calculations. Especially SBAS which is currently in operational permit of a wide range of different flight procedures, offers also more options than conventional navigation systems (Kaleta, 2014).

Such options include possibility of continuous descent operations (CDOs), the flying of curved approaches, adoption "post-in-space" approach, approaches with decision high 200 ft using new LPV-200 possibility. The main incentives for determining new flight procedures for air traffic management are separating arriving, departing traffic and raising overall system efficiency. Reducing noise and pollutant emissions are further key considerations. Compared from approach and landing air traffic system perspective, some of the advantages obtained by SBAS to legacy systems are wide coverage area, low cost for maintenance, suitability for all phases of flight, flexible approach and landing routes, efficiency and cost effectiveness and less susceptibility to environmental conditions. The areas other than the aviation, where SBAS are widely used include some special military applications, agriculture, maritime, railways, land transport and construction applications, geodetic studies and timing standards.

The main drawbacks of conventional systems are both requirement driven such as efficient use of airspace, manpower and training, frequent maintenance for continuous operation and cost driven such as high installation, maintenance and calibration costs. Recent developments in SBAS technology has created a potential to overcome the drawbacks of conventional systems features increased service capacity, high availability and accuracy levels with recent transition to multi frequency capability, which enable SBAS to be used for all flight phases from en-route to landing.

There are currently three such systems in operational use that are of relevance to the management of the aviation sector:

- EGNOS, the European Geostationary Navigation Overlay Service belongs to the European Commission,
- WAAS, the USA's Wide Area Augmentation System,
- MSAS, Japan's Multi-functional Satellite Augmentation System

Russia and India are also developing their own augmentation systems.

Satellite-based navigation with more precision, reliability and flexibility in all phases of flight will enable curved precision approaches instead of the traditional straight precision approach with its limitations, by using more precise, flexible satellite based navigation, thereby enhancing flight safety and convenience making efficient use of airspace. The availability of the European SBAS – EGNOS LPV-200 (Localizer Performance with Vertical guidance) service level was announced last year.

5 LPV AS A TOOL FOR LANDING PROCEDURE SUPPORT

The existence of new satellite service level enables aircraft approaches that are operationally equivalent to ILS CAT I, providing lateral and angular vertical guidance without the need for visual contact with the ground until a Decision Height (DH) of down to only 200 ft above the runway. These new EGNOS – based approaches are considered ILS look-alike but without the need for expensive ground infrastructure required for ILS.

LPV operations are designed to be compatible with existing flight guidance installations and provide lateral and vertical course guidance which varies in sensitivity with distance from the runway, much like an ILS (Kaleta, 2015). They are the highest precision GNSS aviation Instrument Approach Procedures. Using current EGNOS SoL service, the pilot is able to take the aircraft down "blind", without visual contact to the ground, to as low as 200 feet minima – LPV-200 – (APV, ILS look-alike approach) with a ground infrastructure limited to runway lighting.

The availability of the EGNOS LPV-200 service level was announced 29th of September 2015 at the annual EGNOS Service Provision workshop in Copenhagen. It is to be underlined the promulgation of RNP approach down to LPV minima as low as 200ft does not represent any change in the way these approach procedures are currently flown or implemented. EGNOS LPV-200 based approaches, lowered from LPV-250, guarantee all the advantages provided by an ILS CAT I approach with the airspace design flexibility of a PBN approach.

EGNOS LPV-200 supports civil aviation operations during approaches to airports and helipads. The service requires no upgrade to an airport's ground infrastructure or to existing certified EGNOS receivers.

The first LPV-200 procedures are currently under development in the UK, Austria and France. LPV200 and LPV(APV-I) share some requirements such as the Horizontal Navigation System Error (HNSE), Horizontal Alert Limit (HAL), Integrity Risk, Time to Alert and Continuity. LPV200 defines its own series of more stringent performance requirements such as Vertical Navigation System Error (VNSE) of 4 m (95%) and Vertical Alert Limit (VAL) of 35 m.

6 METHOD OF CFIT PROBABILITY ESTIMATION

6.1 *General concept of the method*

As it was mentioned before, accidents of CFIT category belong to the group of most dangerous safety issues. Air traffic management agencies and organizations pay special attention to eliminate them. From the possibility of LPV-200 procedures implementation point of view, it is essential to evaluate how the probability of CFIT (PoC) will change after their implementation. It is important to consider the specific airport, particular air crew and meteorological conditions in analysis. Calculations of statistical nature have less importance in this case.

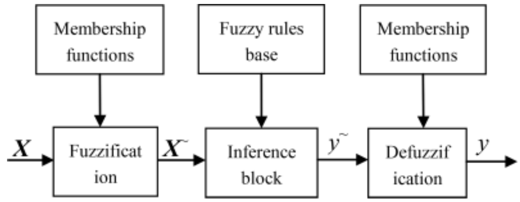

Figure 1. General structure of the fuzzy inference system.

To calculate the PoC is not an easy thing. Basic problem is connected with strong importance of human factor as a main element affecting formation of the air accident of CFIT category. Any analyses of the crew's fault probability are subject to a high degree of uncertainty. They are inaccurate and largely subjective. This causes the need to use methods suitable for existing uncertainty. Closer problem analysis shows, that probabilistic methods are not very useful, but it should be considered to look for solutions in the fuzzy or rough methods areas (Dubois & Prade, 1992, Greco et al., 2001; Zadeh, 1973).

In this paper we propose to assess PoC with a method based on fuzzy inference systems. Generally, this kind of systems is based on the concept that as input and output we have crisp (not fuzzy) values, but the knowledge which allows us to assign output values for the given input values is described based on fuzzy inference rules, usually acquired from the experts. General fuzzy inference system idea is shown in Figure 1 (Siler & Buckley, 2005).

For the input of the fuzzification block we give unfuzzy values $\boldsymbol{X}$ obtained through observation or measurements. In the fuzzification block, based on the specified membership functions, they are associated with the linguistic variables. The fuzzy values $\boldsymbol{X}$ constitute the input for the inference block. This block uses the base of fuzzy rules which in our case are created by experts, practitioners in the field of airport safety. The inference block, on the basis of fuzzy prerequisites and all the fulfilled rules, specifies the conclusion in the form of a linguistic variable $y^{\sim}$. This conclusion is an input for the defuzzification block which on the basis of the specified membership function associates the fuzzy value with the output unfuzzy value y. It constitutes the result of the operation of the fuzzy inference system.

The inference block uses knowledge base in the form of conditional sentences, where both the prerequisites and the conclusions are formulated with the use of linguistic variables. A linguistic variable is a variable whose values are either words or sentences in a natural or artificial language. These words or sentences will be called the linguistic values of a linguistic variable. Details are provided in particular sections which describe subsequent linguistic variables. Also, a graphical interpretation of particular values of each of the linguistic variables is presented. A fuzzy set will denote a set of

$$A = \{(x, \mu_A(x)) : x \in X, \mu_A(x) \in [0,1]\} \tag{1}$$

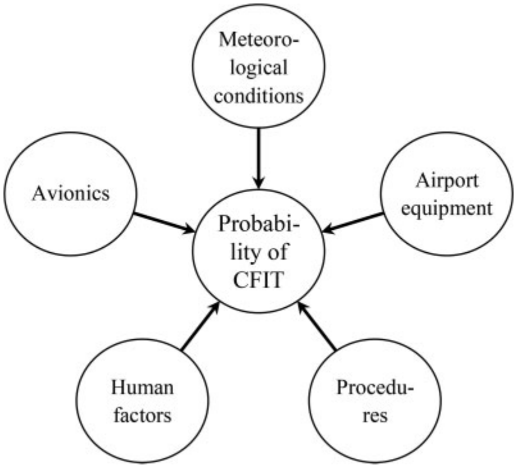

Figure 2. General structure of the model for PoC calculation.

where μ_A is the membership function of this set. The main idea of the fuzzy logic is the partial membership of an element to the set. While in the classical set an element belongs to the set or not, so much in the fuzzy set an element may belong to it to some extent. This mechanism allows for the expression of uncertainty and imprecision of knowledge we possess.

6.2 *Hierarchical model for CFIT probability evaluation*

Probability of CFIT depends on many factors. There is no possibility to develop a method based on mathematical function describing the influence of particular factors on PoC. That is why in this paper a fuzzy model of hierarchical structure is used, which general idea is shown in Figure 2.

Five main factors influencing PoC were distinguished:

- aircraft avionics,
- meteorological conditions,
- airport navigational equipment,
- approach and landing procedures,
- human factor.

Each of these modules constitutes a local fuzzy inference system with several inputs (not shown in Figure 2) and one output. Outputs from these local models are inputs for the final fuzzy inference system in which calculation of PoC will be done. The inference system uses expert knowledge which is usually expressed in natural language, in inaccurate way, so the output value of the whole system will be linguistic CFIT probability, expressed according to a scale proposed in (Lower et al., 2016). The scale is shown in Figure 3.

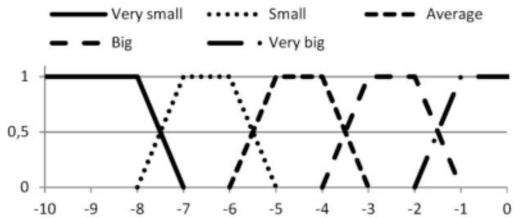

Figure 3. Linguistic variable *PoC* in logarithmic form.

6.3 *Local model meteorological conditions*

All the local models of the proposed hierarchical structure are developed using the same scheme. As the inputs we take measurable factors, determined based on the observations or assessments made by the expert. Of course it is possible to use a group of experts which allows for higher objectivity of the values. In such a case aggregation of the knowledge obtained from experts is necessary. In future research this aggregation will be done using the method described in (Skorupski, 2014). In case of incompatible inference rules, it is possible to use automatic verification method proposed in (Skorupski, 2015b).

To illustrate the method, the local model *Meteorological conditions* will be described in more details.

The input values for the model are:

- *Visibility*. We estimate it in kilometers, the scale range is from 0 to 20 km.
- *Cloudiness*. Evaluation scale is from 0 to 8 which is equivalent to the typical scale: 0/8, 1/8, …, 8/8.
- *Clouds base*. We estimate it in feet, the scale range is from 0 to 3000 ft.
- *Force and direction of the wind*. To evaluate this parameter a scale of three descriptive values is used: *without impact*, *hindering*, *preventing*.

According to the general idea of fuzzy inference systems (Figure 1) each of the input values must be transformed into a fuzzy set according to predefined membership functions. Each fuzzy set will represent a value of linguistic variable. For example, for the input variable *Visibility* trapezoidal membership functions shown in Figure 4 were used. This linguistic variable may take one of five values: *low*, *average*, *good*, *very good*, *CAVOK*.

Linguistic input variable *Cloudiness* was also described by trapezoidal membership functions and may take one of the values: *none*, *small*, *average*, *large*, *full*.

Linguistic variable *Clouds base* shown in Figure 5 has also trapezoidal membership functions. This variable can have values: *low*, *average*, *high*, *very high*.

Variable *Force and direction of the wind* takes values represented by fuzzy singletons named: *without impact*, *hindering*, *preventing*.

Output variable of fuzzy inference model *Meteorological conditions* was determined by triangle membership functions shown in Figure 6.

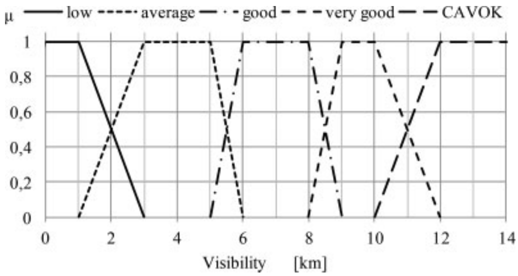

Figure 4. Membership functions of the values of *Visibility* input linguistic variable.

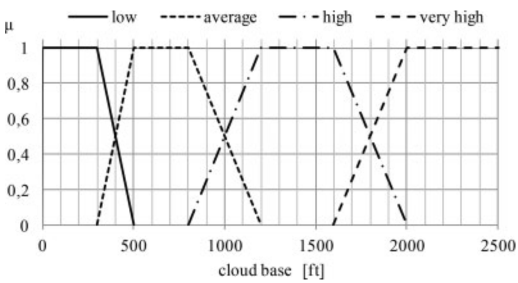

Figure 5. Membership functions of the values of *Cloud base* input linguistic variable.

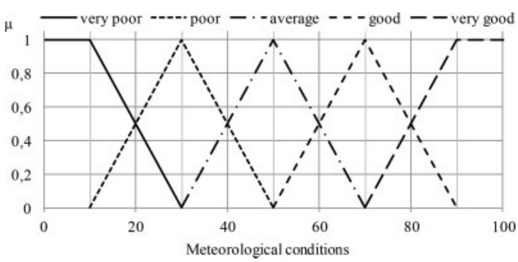

Figure 6. Membership functions of the values of *Meteorological conditions* output linguistic variable.

Fuzzy inference system is supplemented by fuzzy inference rules which are the representation of the experts knowledge. Table 1 shows some example inference rules for *Meteorological conditions* model.

6.4 *Other local models*

The others local models: *Avionics*, *Human factors*, *Procedures* and *Airport equipment* – were developed using the same rules. Due to the paper volume their description will be omitted. General conclusion from these models development is that special attention should be paid to the process of acquiring of expert knowledge, especially to resolving any inconsistence that is often a problem when an expert knowledge is used.

Local model *Avionics* is based on determining individual aircraft's avionics systems availability. Importance level is different for each system and is reflected in aircraft's equipment evaluation. Systems taken into consideration are: TAWS (Terrain Awareness and Warning System), EGPWS (Enhanced Ground Proximity Warning System), SBAS (Satellite-based augmentation systems), VOR/DME (VHF Omnidirectional Range/Distance Measuring Equipment) + ILS (Instrument Landing System), GPS (Global Positioning System), HUMS (Health and Usage Monitoring Systems), FMS (Flight Management System), glass cockpit, weather radar and radio station. As a result of using appropriate fuzzy inference system we obtain an evaluation of aircraft's avionics in numerical scale ranging from 0 to 100 like in the case of the local model *Meteorological conditions* (Figure 6).

Table 1. Fuzzy inference rules for *Meteorological conditions* model.

Visibility	Cloudiness	Cloud base	Force and direction of the wind	Meteorological conditions
CAVOK	none	very high	without impact	very good
very good	large	high	hindering	good
good	large	low	preventing	very poor
average	full	low	without impact	average average
low	average	very high	hindering	poor

Local model *Airport equipment* is based on similar rules as in *Avionics* model. The systems considered in final evaluation are: DGNSS – GBAS, ILS, MLS, VOR/DME, NDB. It is obvious that possibility to use any kind of equipment (like ILS) depends on avionics mounted on the aircraft. In case of lack of corresponding equipment, even very good navigational equipment available at the airport does not improve PoC value. These relations were mapped in fuzzy inference rules.

Local model *Procedures* used to evaluate approach and landing procedures was developed based on binary variable determining if particular procedure was used.

For the *Human factors* local model, the most important in CFIT probability context is the crew situational awareness. This is widely known problem and it is known that pilot's situational awareness depends on many factors like: pilot's knowledge of present position in space, correct equipment readings, environment etc. As the psychological analysis is not the goal of this paper, present model's version use only synthetic evaluation of the situational awareness. Future research will develop this part of the model.

The last stage of the process of development of the model for evaluation of CFIT probability in case the approach and landing LPV-200 procedures are used is the determination of fuzzy inference rules for the final model *PoC*. For the individual equipment combination, meteorological conditions, and avionics availability, usage of LPV-200 procedure may result in different *PoC* values.

6.5 *Implementation – computer tool*

Local fuzzy model *Meteorological conditions* was implemented in SciLab 5.4 environment with Fuzzy Logic Toolbox add-on.

Initial experiments carried out using the created software allowed to conclude its usefulness in the process of calculation of CFIT probability. Final version will contain the implementation of all the local models described in this paper.

7 SUMMARY AND FINAL CONCLUSIONS

In this paper a fuzzy model for calculation of probability of CFIT was proposed. Its full implementation will allow us to analyze effects of LPV-200 procedures implementation for air traffic safety. It is obvious that implementation of such procedures is a real chance for small airports development, which in practice cannot afford to install typical navigational assistance solutions, such as ILS.

This paper shows current state of research in which we have developed a concept of a hierarchical fuzzy inference system, a concept of local models structure and more detailed specification of one of these models – *Meteorological conditions*. Other parts of the model and its full computer implementation are being developed at the moment.

The tests carried out so far show that this particular tool is really useful and convenient. Its full implementation will allow to maintain risk analysis, where the main factor will be evaluation of the CFIT probability. What is especially important from practical point of view, that analysis will be done for specific airport, specific meteorological conditions, specific avionics, specific air crew and particular approach and landing procedure.

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