A fuzzy inference approach to analysis of LPV-200 procedures influence on air traffic safety

Wojciech Kaleda, Jacek Skorupski

Naval Aviation Brigade Command, Gdynia, Poland
Warsaw University of Technology, Faculty of Transport, Warsaw, Poland

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ABSTRACT

Introducing new technical and organizational solutions in air transport requires demonstrating that the level of safety will not be reduced. The LPV-200 (Localizer Performance with Vertical Guidance) approach for landing procedures represent a great opportunity for development of small, poorly equipped airports, as they permit precise landing without costly investment in the ILS (Instrument Landing System). The aim of this paper is to assess the effects of the introduction of LPV-200 procedures for air traffic safety which was determined by the probability of a CFIT (Controlled Flight Into Terrain) accident – PoC. Factors affecting PoC are of a diverse nature, some of which are subjective and cannot be expressed precisely. Therefore, PoC assessment uses fuzzy logic methods, and more specifically hierarchical fuzzy inference systems, with a knowledge base obtained from experts. As a result of simulation experiments, PoC was determined for airports with various levels of navigational equipment. It was also found that the introduction of LPV-200 procedures allows the reduction of PoC, with the highest effect being achieved for the least equipped airports. Also, in the event of failure of the main approach assistance system ILS, the use of LPV-200 procedures allows maintaining PoC at the same or close to the basic value level. The results of our research indicate that the introduction of LPV-200 procedures is clearly positive for the commercial use of small, less equipped aerodromes. We have shown that thanks to employing LPV-200 procedures it is possible to keep the PoC at a level similar to typical commercial airports.

1. Introduction

Airspace near airports is characterized by a high congestion of air traffic. Approach procedures are complicated, which causes a huge workload, both for pilots and air traffic controllers. Therefore, the approach and landing flight phases are the most crucial for air traffic safety. Many occurrences of accidents 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 (EASA, 2012). These accidents usually involve fatalities and casualties. Most landing approach procedures are supported by ILS (Instrument Landing System), which makes it possible to continue an approach without visual contact with the ground to a specified height. However, many airports, especially smaller ones, cannot afford ILS installation. This brings forth the problem of how to develop procedures which allow an ILS-like approach with a ground infrastructure limited to runway lighting. Simultaneously a question arises – is this even 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). It should be ensured that the new solutions introduced do not cause a drop in the level of safety.

In this paper, we deal with the safety analysis (expressed in terms of the PoC) of the LPV-200 procedures (Localizer Performance with Vertical guidance). Operationally, they are equivalent to ILS category I, providing lateral and angular vertical guidance without the need for visual contact with the ground until a Decision Height of only 200 ft above the runway. They are based on satellite navigation supported by a ground-based system such as the European Geostationary Navigation Overlay Service EGNOS (Kaleta, 2014, 2015).

1.1. Safety of airport operations

Air traffic around airports usually takes place using predefined trajectories defined by Standard Instrument Departure Route (SID) and Standard Arrival Route (STAR) procedures. They are designated by a list of waypoints, for which also recommended cruising altitude and speed limit can be determined. Aircraft approach and landing phases are the source of almost half the deaths in aviation accidents worldwide (IATA, 2015b). In contrast, the duration of the approach and landing phases typically is only 16 percent of the average total flight time. There is a rich set of literature in which various aspects of safety in this area are analyzed and used to study the risk associated with specific events in airport areas.

The method of general safety assessment around the airport was proposed by Hadjimichael (2009). It allows searching for these types of events near the airport, which are the most often causes of accidents in aerodrome traffic. Skorupski (2016) analyzed the risk related to Runway Incursion-type events by proposing a fuzzy risk matrix to express the level of safety. A similar method in which Petri nets were used to assess safety and its measure is the probability of an accident was presented in (Skorupski, 2015). Wong et al. (2009) proposed a methodology for assessing the frequency of accidents near the airport using multivariate logistic regression. The method allows estimation of the frequency of events divided into several types, from which the landing overrun and landing undershot can be used as an indicator of safety assessment around the airport. This paper deals mainly with accidents of a CFIT type, meaning accidents in which the aircraft is still able to fly and under the control of the flight crew. There are numerous causal and contributing factors of such events. Typically, the causes are attributed to flight crew or human error, such as non-compliance with established procedures, inadequate flight path management, lack of vertical or horizontal position awareness in relation to terrain, non-stabilized approaches and failure to initiate a go-around when a go-around was necessary (Kharoufah et al., 2018; Li et al., 2018). The characteristics of the terrain around the airport are significant for the absolute value of the probability of CFIT. Our goal is not to compare the absolute values of airports safety but rather an analysis of how the use of LPV-200 procedures affects the safety of a specific airport, and even in a specific traffic situation. Therefore, we assumed that the impact of terrain characteristics on CFIT probability will be mapped not directly by the variable determining the occurrence of terrain obstacles, but rather indirectly through the Situational awareness variable saying about the pilot’s awareness of these obstacles and the ability to use this knowledge.

The absence of precision approaches has also been noted as a factor in CFIT accidents (IATA, 2015a). Oster et al. (2013) presented a more general overview of the causes and effects of aviation accidents, including those of the CFIT category. Ken (2013) attempted to determine the risk of a CFIT type accident based on multicriteria group assessment by experts. The proposed method determines the estimation of the risk in a scale, which mainly allows a relative comparison of the CFIT risk when using different landing approach procedures. Our paper extends this research by using a hierarchical fuzzy inference system, using well-defined quantities with physical linguistic interpretation as input variables, and expressing the PoC in the terms of probability.

1.2. Satellite-based systems for air traffic support

In today’s aviation, conventional ground-based, or inertial on-board systems have 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, like ILS, can also support very precise approach and landing capability, there are still some drawbacks related with these systems which have prompted users to search for better alternatives.

Global Navigation Satellite Systems (GNSS) stands as a prominent alternative to existing systems in terms of usability in all flight phases, providing approaches to airfields which lack a navigational aid infrastructure. However, due to various types of errors 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. Thus, supporting systems, namely the satellite-based augmentation system (SBAS) and the ground-based augmentation system (GBAS), present cost-effective solutions, meeting the performance requirements, also for the landing phase of flight (Fellner et al., 2012; Kaleta and Skorupski, 2016). Especially SBAS, which is currently operationally permitted for a wide range of different flight procedures, offers more options than conventional navigation systems (Kaleta, 2014). Dautermann et al. (2015) suggested the need to develop such approach procedures, especially for airports where there are numerous terrain obstacles, or where the traffic conditions are complicated. Innsbruck and Egelsbach are the examples of such airports (Schaad, 2012; Dautermann et al., 2015). Innsbruck Airport, located in Austria, has complicated and difficult approach procedures due to the surrounding terrain such as mountains, prohibiting certain aircraft types from operating at the airport. The procedures are complicated because of low visibility conditions, vicious winds and currents present throughout the approach and landing process. These difficulties require pilots to have special training. Egelsbach Airport is located in Germany within a Class D airspace in the Frankfurt International Airport control zone. The airfield is located underneath class C airspace commencing at the height of 1500 ft intended to protect IFR traffic operating in and out of Frankfurt. Many of departure and arrival routes cross over or
near the Egelsbach’s runway. This makes problems for the approach, landing and take-off procedures. Dautermann et al. (2015) designed and tested two such procedures in flight at the airports of Saarbrücken and Egelsbach. Results show that the track can be followed with high precision both in manual and in automatic flight with a light piston twin aircraft as well as a fast business jet.

1.3. Concept of the study

A review of the literature indicates that there is no effective method that would allow to assess the impact of the implementation of LPV-200 procedures on air traffic safety. We propose to express this safety by the Probability of a CFIT accident (PoC) as the most directly related to navigational problems in the final approach and landing phase. Our article extends existing research by creating a generic model that allows PoC to be estimated considering many influencing factors. These are both objective and measurable factors, but also subjective and dependent on human factor. These factors were determined, the fuzzy model built, and then experiments were conducted to find how the probability of CFIT will change after implementation of LPV-200 procedures.

This article is a continuation of a previous article by the authors (Kaleta and Skorupski, 2016), where only meteorological conditions were discussed. The research presented here has been extended by discussing the remaining local fuzzy models, with factors influencing PoC being presented slightly differently, which results in a slightly different overall structure of the model. Additionally, in this work we present a complete computer implementation of the model, forming a research tool that allowed us to perform many simulation experiments. The test results allowed us to obtain some general conclusions as to the feasibility and desirability of applying the LPV-200 procedures at airports of various types.

The remaining part of the paper is structured as follows: Section 2 discusses the method for calculating PoC. General information about fuzzy inference systems, the general concept of the PoC determination system, individual local models and corresponding linguistic variables as well as the computer implementation of the model are described. Section 3 presents the method of model validation and simulation experiments. The experiments consist in the determination of PoC for various types of airports and the assessment of the impact of LPV-200 procedures implementation in both typical conditions and in the event of failure of the basic navigation system. Section 4 contains the summary and final conclusions.

2. Method of CFIT probability estimation

2.1. Fuzzy inference systems

As mentioned previously, accidents from the CFIT category belong to the group of most dangerous safety issues which air traffic management agencies and organizations pay special attention to eliminate. For the possibility of implementing LPV-200 procedures it is essential to evaluate how the probability of CFIT will change after such procedures are implemented. Our goal is not to determine the average value of PoC, but its value for any possible combination of input variables included in the model. In the analysis, it is important to consider the specific airport, air crew and meteorological conditions that exist.

Calculation of PoC is a challenging task. The basic problem relates to the strong importance of the human factor as being a main element affecting formation of air accidents of the CFIT category. Any analyses of the probability of the crew’s fault are subject to a high degree of uncertainty and are often inaccurate and largely subjective. This creates the need to use methods suitable for existing uncertainty. Closer problem analysis shows, that fuzzy or rough logic methods should be considered to look for solutions (Dubois and Prade, 1992; Greco et al., 2001; Zadeh, 1973). They allow using knowledge that is expressed in an imprecise way to obtain accurate results. What is important, the knowledge used is useful and accurate, but cannot be expressed by means of strict functional dependencies.

In this paper we propose to assess PoC with a method based on fuzzy inference systems. Generally, this kind of system is based on the concept that as input and output we use crisp (not fuzzy) values, but the knowledge which allows us to calculate output values for the given input values cannot be described precisely, so we use fuzzy inference rules, usually acquired from the experts in the field studied. The general idea of the fuzzy inference system is shown in Fig. 1 (Siler and Buckley, 2005).

For the input of the fuzzification block we give unfuzzy values $X$ 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 $X^\sim$ constitute the input for the inference block. This block uses the fuzzy rules base which in our case are created by expert practitioners in the field of airport safety. The inference block, based on 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 based on the specified membership functions.
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 a 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 the subsequent linguistic variables. Also, a graphical interpretation of values of each of the linguistic variables is presented. A fuzzy set will denote a set of

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

where \( \mu_A \) 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 either belongs to the set or not, whereas in the fuzzy set an element may belong to the set to some extent. This mechanism allows for the expression of uncertainty and imprecision of knowledge we possess.

2.2. General concept of the method

Probability of CFIT depends on many factors. Some, such as the human factor are subjective or cannot be expressed accurately. There is no possibility to develop a method based on mathematical function describing the influence of some particular factors on PoC. However, for experts it is possible to estimate the impact of certain factors on PoC by using descriptive terms for this purpose. That is why in this paper a fuzzy model of hierarchical structure is used, and the general idea is shown in Fig. 2.

Output variable Probability of CFIT \( (z_{PoC}) \) depends on four inputs variables:

- Meteorological conditions \( (y_{mc}) \), which is output of local inference system with four input variables: Visibility \( (x_v) \), Cloudiness \( (x_c) \), Clouds base \( (x_{cb}) \), Force and direction of the wind \( (x_w) \).
- Navigational equipment \( (x_{ne}) \), which describes both avionics equipment of the aircraft and navigational equipment of the airport,
- Navigational accuracy \( (x_{ap}) \) characterizing the accuracy that can be achieved when using a specific navigation procedure,
- Human factor \( (y_{hf}) \), which is also the output of the local inference system, with three inputs: Training \( (x_t) \), Experience \( (x_e) \) and Situational awareness \( (x_{sa}) \).

Details on the values of all linguistic variables and the method of constructing membership functions are presented in Sections 2.3–2.6. Outputs from the 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 an inaccurate way. The output value of the whole system will be expressed according to a scale proposed by Lower et al. (2016). The scale is shown in Fig. 3.

2.3. Local model Meteorological conditions

The task of the local fuzzy inference model Meteorological conditions is to provide an aggregated assessment of weather conditions, with particular attention placed on such values that may have a fundamental impact on air traffic safety, and more precisely on the occurrence of a CFIT accident. Therefore, difficult weather conditions were distinguished both in determining the form of membership functions of linguistic variables as well as in creating the knowledge base, i.e. low visibility, high cloudiness, low cloud base and strong wind.

The input values for the Meteorological conditions model are (Kaleta and Skorupski, 2016):
Visibility. Estimated 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. Estimated 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 (Fig. 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 Fig. 4 were used. This linguistic variable may take one of five values: low, average, good, very good, CAVOK. Visibility is such an important variable in the context of the PoC that for each airport, each aircraft as well as each pilot, a minimum value has been determined, below which continuation of the landing operation is unacceptable.

Linguistic variable Cloudiness specifies the level of cloudiness in the airport area. Its impact on PoC is slightly smaller than the variable Visibility, and indirect. Landing may be carried out even with full cloudiness unless the cloud base is too low. However, in the case of unfavorable values of this variable one should expect both rainfall, which decreases horizontal visibility as well as lowering of the cloud ceiling. Both cases may pose a threat to air traffic safety. The linguistic variable Cloudiness was also described by trapezoidal membership functions. One of the following values is used: none, small, average, large, full.

The linguistic variable Clouds base describes the second very important variable in the context of safety of landing operations. As with the Visibility variable, requirements are formally defined for Cloud base, the fulfillment of which is necessary to be able to perform the landing operation. Linguistic variable Clouds base shown in Fig. 5 also has trapezoidal membership functions. This variable can have values: low, average, high, very high.

The linguistic variable Force and direction of the wind is important in the context of PoC as a very strong wind, especially blowing in the direction transverse to the direction set by the runway, can disrupt or even prevent the landing operation. In the event of non-compliance with the limitations on the transverse component of surface wind, it can even cause various types of accidents, including those of the CFIT category. Due to the difficulty of including in the analysis the exact values of wind force and direction, in our model, variable Force and direction of the wind takes values represented by fuzzy singletons named: without impact, hindering, preventing. These values will be determined based on expert assessments.

As already mentioned, the purpose of the Meteorological conditions model is the aggregated assessment of weather conditions at the landing airport. Output variable of fuzzy inference model Meteorological conditions was determined numerically by using the
Mamdani type of model. When this variable is interpreted as an input to the PoC model it will be determined by triangle membership functions shown in Fig. 6.

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

2.4. Linguistic variable Navigational equipment

Limit values are defined regarding meteorological conditions, below which, continuation of the landing operation is unacceptable. These values depend to a large extent on the navigational equipment available at the airport. It is worth noting, that to use it, the aircraft must be equipped with appropriate on-board components, the pilot must be properly trained, and all devices must be operational.

The essence of the linguistic variable Navigational equipment is therefore an integrated evaluation of the equipment including two components. First is aircraft avionics and second is airport navigational equipment. Systems which have the highest impact on precision of approach and landing procedures were considered. These are: EGPWS (Enhanced Ground Proximity Warning System) or GPWS (Ground Proximity Warning System), SBAS (Satellite-based augmentation systems), VOR/DME (VHF Omnidirectional Range/Distance Measuring Equipment), MLS (Microwave Landing System) or ILS (Instrument Landing System), DGNSS (Differential Global Navigation Satellite System) with GBAS (Ground-Based Augmentation System) and FMS (Flight Management System).

Compatible systems in both components are necessary for the proper use of available resources. In case of lack of corresponding equipment, even very good navigational equipment available at the airport does not improve PoC value. Therefore, in the Navigational equipment model both components will be treated together.

The base for determination of Navigational equipment variable is a numerical scale ranging from 0 to 100, which represents a combined estimation of the level of aircraft’s avionics and airport equipment. For this evaluation, the following simple mathematical model will be defined.

\[ S = [s_j], j = 1, \ldots, J \]  

(2)

will describe the set of considered navigational systems, and

\[ AC = [ac], i = 1, \ldots, I \]  

(3)

will be a set of aircraft using the airport. For each aircraft, we will define a function that determines the availability of a given system

\[ e: AC \times S \rightarrow [0, 1] \]  

(4)

where \( e(ac, s_j) = 1 \) means, that \( i \)-th aircraft is equipped with avionic component of \( j \)-th navigational system and this system can be used at the considered airport (is operational and turned on).

The importance level is different for each system and is reflected in the aircraft’s and airport equipment evaluation. For this purpose, we will define a vector of weights describing the importance of the system for the possibility of avoiding CFIT.
Individual weights will be adopted based on expert assessments in the way that the maximum assessment of existing equipment will be equal to 100.

Having information on the available avionic equipment and the weight of each system, we can determine the final quantitative assessment of the navigational equipment, which for the \( i \)-th aircraft is given by the equation

\[
EQ(ac) = \sum_{j=1}^{n} w_j e(ac, s_j)
\]

The coefficient \( EQ \) is the base for determining linguistic variable \textit{Navigational equipment}, which can take one of five values: very poor, poor, average, good, very good. Membership functions of the corresponding fuzzy sets are shown in Fig. 7.

2.5. Linguistic variable Navigational accuracy

Approach for landing procedures were designed to support aircraft performing operations in instrumental flight mode. These procedures are extremely important in the context of PoC because they allow aircraft to perform landing operations in the immediate vicinity of the ground in the event of lack of runway visibility. The use of the procedure is determined by on-board equipment and training, but also by the availability of an appropriate infrastructure.

We divide the approach for landing procedures into precision and non-precision approaches depending on the navigational accuracy that can be achieved. Precision procedures include:

- GLS (GBAS Landing System), which uses GNSS data and amendments from a ground reference station located at the airport, which provides both geographical position correction and monitoring of system integrity,
- ABAS LNAV VNAV (Aircraft-Based Augmentation System), using data from GNSS systems and amendments from aircraft-based equipment,
- APV (Approach with Vertical Guidance), providing a vertical guidance approach, where navigational corrections come from the European EGNOS augmentation system,
- ILS (Instrument Landing System), a radio navigation landing system which provides both vertical and angular guidance to the approaching aircraft,
- MLS (Microwave Landing System), radio-based approach and landing system based on microwaves, like the ILS system.

Non-precision landing approach systems include:

- APV BARO VNAV, approach and landing with vertical guidance, where navigational corrections come from the European EGNOS augmentation system, but using barometric altitude data during the approach to landing,
- SBAS (Satellite-Based Augmentation System), a long-range navigation system using data coming from GNSS improved by the use of geostationary satellites,
- VOR/DME RNAV – an approach and landing system based on two VOR (VHF Omnidirectional Radio-range) beacons and DME.
Table 2
Navigational accuracy and integrated coefficient $A$ for precision approach.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Accuracy [m]</th>
<th>$A$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>horizontal</td>
<td>vertical</td>
</tr>
<tr>
<td>GLS</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>ABAS LNAV VNAV</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>APV</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>MLS</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>ILS</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>GBAS</td>
<td>16</td>
<td>6</td>
</tr>
</tbody>
</table>

(Distance Measuring Equipment), providing to the aircraft information on the position and distance to the ground station and the information obtained from GNSS system,

– DME/DME RNAV, approach and landing system using data from DME and GNSS system,
– GNSS RNAV, system based on area navigation and data originating from GNSS system,
– GBAS RNAV, based on data from GNSS ground station located at the airport that provides geographical position correction and monitors the system integrity,
– VOR/DME, approach and landing system operating similarly to VOR/DME RNAV, but not using data from GNSS system,
– VOR, approach and landing procedure based on VOR beacon only,
– NDB (Non-Directional Beacon) – non-precision approach procedure using a non-directional radio beacon as the only source of information about aircraft’s position.

Each of the mentioned systems is characterized by some acceptable error in indicating the position. This error is substantially different with respect to the horizontal position and altitude of the aircraft. In our model, the basis for determining the linguistic variable *Navigational accuracy* will be the integrated coefficient of navigational accuracy $A$, considering both ranges of inaccuracy. Due to the differences in accuracy, it was assumed that the weight of vertical accuracy in this indicator is nine times greater than the weight of the horizontal position accuracy. This ratio reflects the average ratio of positioning accuracy. Table 2 presents the horizontal and vertical accuracy as well as the value of the $A$ coefficient for precision approach procedures and Table 3 accuracy for the non-precision ones.

Based on the integrated navigational accuracy coefficient $A$, the membership functions of values of linguistic variable *Navigational accuracy* were determined, as shown in Fig. 8.

2.6. Local model Human factor

The human factor is the basic term defining human behavior at work and in private life. In most cases this term is perceived negatively due to its use mainly in the context of human error. However, it must be remembered that it also contains all the positive aspects of human behavior.

Human (pilot) behavior is essential for PoC. Knowledge of rules and procedures, the ability to accurately perform landing operations, but also to comply with all safety rules resulting from the awareness of the threat, largely determine the possibility of a CFIT type accident. Therefore, this model has a significant role in the PoC assessment.

There are three main factors that influence the operation of the aircrew in relation to the safety of landing operations and therefore the likelihood of a CFIT accident. These are *Training, Experience* and *Situational awareness*. These factors will be analyzed in this section.

The linguistic variable *Training* characterizes the flight crew member in terms of the ability to perform aviation tasks. In the model

Table 3
Navigational accuracy and integrated coefficient $A$ for non-precision approach.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Accuracy [m]</th>
<th>$A$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>horizontal</td>
<td>vertical</td>
</tr>
<tr>
<td>APV BARO VNAV</td>
<td>556</td>
<td>30</td>
</tr>
<tr>
<td>SBAS</td>
<td>220</td>
<td>20</td>
</tr>
<tr>
<td>ABAS</td>
<td>220</td>
<td>50</td>
</tr>
<tr>
<td>VOR/DME RNAV</td>
<td>110</td>
<td>23</td>
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<tr>
<td>DME/DME RNAV</td>
<td>1852</td>
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</tr>
<tr>
<td>GNSS RNAV</td>
<td>556</td>
<td>50</td>
</tr>
<tr>
<td>GBAS RNAV</td>
<td>220</td>
<td>20</td>
</tr>
<tr>
<td>VOR/DME</td>
<td>34</td>
<td>30</td>
</tr>
<tr>
<td>VOR</td>
<td>34</td>
<td>30</td>
</tr>
<tr>
<td>NDB</td>
<td>122</td>
<td>30</td>
</tr>
</tbody>
</table>
we use three values of this linguistic variable: low, medium and high. To determine the value of this variable, we use:

– the time that has elapsed since the last flight,
– the time since the last flight simulator training which is a valuable index in relation to crew capabilities to cope with emergencies and
– the time from the last check ride, which consists in checking the knowledge and skills of the pilot by an experienced instructor during a flight.

The value of the Training linguistic variable is determined based on expert knowledge implemented as a local fuzzy inference system. Details of this fuzzy model can be found in (Skorupski and Wiktorowski, 2015).

The linguistic variable Experience assumes three values: small, medium and large. It is influenced by such input variables as:

– the number of years spent on the position (captain or co-pilot),
– the number of hours spent in the air working as an aircrew member and
– hours of flight in relation to the current type of aircraft.

The value of the linguistic variable Experience is determined based on expert knowledge implemented as a local fuzzy inference system. Details of this fuzzy model can be found in an earlier work by Skorupski and Wiktorowski (2013).

As for the Human factor local model, crews situational awareness is a very important element in the context of CFIT probability. It includes, among others, the crew’s knowledge of:

– the position of own aircraft in relation to the runway; this is particularly important in the case of imprecise approaches,
– terrain in the approach zone; this applies in particular to depressions and elevations in the immediate vicinity of the runway,
– traffic parameters as well as the technical condition and configuration of the aircraft; in particular, of any failures and malfunctions,
– occurrence of special situations around the runway, such as failure of the navigation device, construction works, temporary obstacles, local natural phenomena.

As psychological analysis is not the goal of this paper, the present model’s version uses only synthetic evaluation of the situational awareness. The linguistic variable Situational awareness accepts three values: low, average and high but will be treated as a static parameter of the local model. In fact, to fully determine this variable, it would be necessary to analyze local flight conditions, especially the terrain characteristics in the approach to landing zone and the psychophysical and perceptual abilities of the crew (Blom and Sharpanskykh, 2015; Chatzimichailidou and Dokas, 2015). We plan to carry out such research in subsequent stages of work by expanding the model in such a way that the variable Situational awareness is the output of a separate local fuzzy interference system.

To show the significance of factors affecting the Situational Awareness variable, including the occurrence of field obstacles and complicated approach procedures resulting from traffic conditions, we have analyzed the sensitivity of the Human Factor variable to changes in the Situational Awareness input variable. The result of this analysis is presented in Fig. 9. A similar analysis of the sensitivity of the PoC variable (at fixed values of the remaining input variables) to changes in the Situational Awareness input variable is presented in Fig. 10.

As can be seen, the reduction of situational awareness, resulting for example from the occurrence of terrain obstacles, reduced visibility or failure of on-board and on-ground equipment components, generally reduces the value of the Human Factor variable, and thus increases the resulting value of the PoC variable.

2.7. Model for PoC evaluation

The last stage of the process of the development of the model for evaluation of CFIT probability is the determination of fuzzy inference rules for the final model PoC. For any combination of input variables values the probability of CFIT was estimated by
experts in descriptive way using values of the linguistic variable PoC shown in Fig. 3. The knowledge base was created in the form of fuzzy inference rules. There were 338 rules defined. Some of them are shown in Table 4.

2.8. Implementation - computer tool

All fuzzy local models create a hierarchical structure in which the outputs of one model are inputs for the next. The models were implemented in a SciLab 5.4 environment with a Fuzzy Logic Toolbox add-on, an open source software for numerical computation providing a powerful computing environment for engineering and scientific applications.

In the fuzzy inference systems, the parameters listed in Table 5 were chosen for the determination of linguistic variable values. Information on how the model was validated is presented in Section 3.1 on PoC assessment for large commercial airports.

3. Simulation experiments

Using the developed model and the research tool created, several simulation experiments were carried out. Their plan was as follows:

Table 4

<table>
<thead>
<tr>
<th>Rule number</th>
<th>Meteorological conditions</th>
<th>Navigational equipment</th>
<th>Human factor</th>
<th>Navigational accuracy</th>
<th>PoC</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>average</td>
<td>poor</td>
<td>bad</td>
<td>very poor</td>
<td>big</td>
</tr>
<tr>
<td>73</td>
<td>good</td>
<td>very poor</td>
<td>average</td>
<td>poor</td>
<td>average</td>
</tr>
<tr>
<td>160</td>
<td>good</td>
<td>poor</td>
<td>average</td>
<td>average</td>
<td>small</td>
</tr>
<tr>
<td>332</td>
<td>very good</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>very small</td>
</tr>
</tbody>
</table>
1. Firstly, the PoC was calculated for average, typical conditions occurring in civil aviation. Comparison of the results with the historical data allowed the model to be validated.

2. Subsequently, experiments were carried out in which we studied PoC for smaller airports, less equipped with navigational systems and at the same time used more often by pilots with lower qualifications or experience – for example, with only a private pilot’s license.

3. As the third stage of the experiments, we performed analyses of PoC sensitivity to various values of input variables and the impact of the application of the LPV-200 procedure on these types of airports.

The following sections show the results of these experiments.

3.1. PoC assessment for large commercial airports

To validate the developed model and the created computer software tool, we compared the historical, statistical PoC with the results obtained from our model. Of course, a strict comparison of these values is not possible, because precise mapping (averaging) of conditions that exist at all airports included in the statistical analysis over a long-time horizon is not possible. To do this, it would be necessary to closely map the distribution of atmospheric conditions in time and space, the frequency distribution of the use of the airport by crews with different competencies and the distribution of navigational equipment or applied approach procedures at individual airports included in the analysis. Such a detailed statistical analysis would go beyond the scope of this paper.

For this paper, with the help of expert knowledge, we roughly estimated the percentage share of several characteristic values corresponding to a particular linguistic variable. The results of this estimation are presented in Table 6. The distribution of meteorological conditions was estimated based on Weather Spark (2017) which provides monthly, hourly and daily graphical reports. Airports located in all climate zones have been selected: Reykjavik, Oslo, Warsaw, Budapest, Sofia, Athens, Cairo, Mexico City, San Jose, Bogota, Brasilia, Buenos Aires. Other values are estimates made based on expert opinions.

For each of the defined characteristic values (favourable, poor, unfavorable) we have determined a corresponding, exemplary combination of input values. The sample values representing individual classes are presented in Table 7.

Then, for each combination of the so-defined characteristic values, we determined the PoC using our model. In the next step, we calculated the total PoC value as a weighted average of the PoC and the probability P of a specific combination of characteristic values of the input variables. A part of these calculations is shown in Table 8. MC is an abbreviation of Meteorological conditions, NE stands for Navigational equipment, HF replaces Human factor and NA is a short form of Navigational accuracy.

IATA annual reports (IATA, 2015b) provide the number of CFIT accidents with division into flight phases. For comparison with our model, we assumed the number of accidents that took place during the approaching phase (APR), go-around procedure (GOA) and landing phase (LND). As we are determining probability, these values will refer to the total number of flight operations (number of landings). Historical statistical values are presented in Table 9.

As can be seen, in the following years there is a large variation in the received probabilities. Over the seven years examined, the ratio of the largest PoC to the smallest was at a level of 9:1. Therefore, we assumed that as the correct value for the model we would consider results in a range from $3 \cdot 10^{-8}$ to $3 \cdot 10^{-7}$. As indicated in Table 8, the result from our model falls within this scope and at the same time it is very close to the average PoC value from 2010 to 2016. On this basis we concluded the correctness of the model and computer tool.

<table>
<thead>
<tr>
<th>Linguistic variable</th>
<th>Favourable values</th>
<th>Poor values</th>
<th>Unfavorable values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteorological conditions</td>
<td>60%</td>
<td>30%</td>
<td>10%</td>
</tr>
<tr>
<td>Navigational equipment</td>
<td>80%</td>
<td>15%</td>
<td>5%</td>
</tr>
<tr>
<td>Human factor</td>
<td>70%</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>Navigational accuracy</td>
<td>80%</td>
<td>15%</td>
<td>5%</td>
</tr>
</tbody>
</table>
3.2. PoC evaluation for local and regional airports

We conducted our analysis in terms of the feasibility and sense of implementation of the LPV-200 procedures. It is obvious that such action may bring greater benefits to small, local airports where there is no economic justification for equipping them with advanced navigation systems. For the analysis of traffic safety, we considered several scenarios. They will be described in a similar way as in Section 3.1, for typical conditions at large commercial airports.

The following research plan was adopted:

1. Scenario 1 – a small, poorly equipped airport, with a large share of operations performed by inexperienced pilots.
2. Scenario 2 – a regional, medium-sized airport serving mainly commercial traffic is subjected to study.
3. Scenario 3 – a military aerodrome with minimal navigational equipment, what is more, it is characterized by unfavorable meteorological conditions.

3.2.1. Scenario 1 – EPCE airport

Cewice Airport (ICAO code EPCE) is located at an altitude of 151 m a.s.l. The weather conditions based on Weather Spark (2017) indicate that for about 70% of the year there are favourable meteorological conditions for flights, for 20% of the year poor conditions and for 10% unfavorable conditions. The airport is equipped with ILS category III and two non-directional NDB beacons.

The 44th Naval military Air Base is situated in Cewice. Apart from normal operating activities, it conducts a year-long training of
young pilots and improvement flights for the remaining staff in school flights. Therefore, the linguistic variable, Human factor in about 30% of cases has unfavorable values, in 20% weak, and in about 50% favourable values.

For most landings at the EPCE airport, a precision approach with ILS is used (80%), in 17% of landings a non-precision approach using NDB beacons and in about 3% an approach without the use of navigational aids. A summary of the percentage share of the characteristic values corresponding to linguistic variables is presented in Table 10.

The PoC has been determined for these input values, using the proposed model and computer tool in the same way as in Section 3.1. The obtained result of $3.3 \times 10^7$ indicates a PoC more than twice as large as the reference value. This is mainly due to the relatively large share of operations performed by pilots with unfavorable Human factor input linguistic variables. As previously indicated, this airport has relatively poor navigational equipment, however, the ILS system is available, which means that most landings are made based on precise navigation procedures.

### 3.2.2. Scenario 2 – EPGD airport

Lech Wałęsa regional airport in Gdansk (ICAO code EPGD) is located in the northern part of Poland. It has two runways heading 290 and 110, both 2800 m long. The airport’s main users are Wizzair and LOT Polish airlines with connections all over Europe. Each year EPGD serves about 7 million passengers which makes it the third largest airport in Poland.

Weather Spark (2017) indicates that for about 70% of the year there are favourable meteorological conditions for flights, for 20% of the year poor conditions and for 10% unfavorable conditions. The airport is equipped with ILS category II, VOR radio beacon integrated with the DME system and SBAS and FMS equipment.

The airport mostly serves civil commercial air traffic and the share of small business aircraft is low. Therefore, the linguistic variable Human factor in about 80% of cases are favourable values, 15% weak, and only about 5% unfavorable values.

For most landings at EPGD, a precision approach with ILS is used (94%). A non-precision approach with the SBAS system is used in around 5% of cases, and only about 1% of approaches are made without using navigational aids. A summary of the percentage share of the characteristic values corresponding to linguistic variables is presented in Table 11.

For such defined input values, PoC was determined using the proposed model and computer tool in the same way as in Section 3.1. The result obtained is $1.5 \times 10^8$, an amount which is twice as small as the left boundary of the interval characterizing PoC for typical civil commercial airports. This value is expected because EPGD is an example of a navigationally well-equipped airport with good geographical and meteorological conditions and used mainly for commercial flights by well-trained airline pilots.

### 3.2.3. Scenario 3 – EPDA airport

Darłowo Airport (ICAO code EPDA) is located in the immediate vicinity of the shoreline, therefore the annual characteristics of weather conditions are quite poor with favourable conditions occurring only about 50% of the year, weak conditions about 20%, and unfavorable around 30%. The only navigational equipment is an NDB beacon system.

EPDA is a military airport where mainly Navy helicopters are stationed which includes 24-h on-call SAR duty. Year-round training of flight personnel is carried out, therefore the distribution of the linguistic variable Human factor in 30% of cases is unfavorable, in 20% weak, and in about 50% favourable.

For most cases of landing at the EPDA airport, a non-precision approach using NDB beacons is performed (90%) and about 10% of approaches are made without the use of navigational aids.

A summary of the percentage share of the characteristic values corresponding to linguistic variables is presented in Table 12.

For the input variables defined in this way, the PoC has been determined using the proposed model and computer tool in the same way as in Section 3.1. The result obtained is $1.5 \times 10^6$. This value is much higher than for typical commercial airports, which should not come as a surprise considering the lack of navigational equipment, a large share of poorly trained pilots and frequent unfavorable meteorological conditions. In the context of such high value of PoC, the possibility of using the EPDA airport for civil flights, and

<table>
<thead>
<tr>
<th>Linguistic variable</th>
<th>Favourable values</th>
<th>Poor values</th>
<th>Unfavorable values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteorological conditions</td>
<td>70%</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>Navigational equipment</td>
<td>97%</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>Human factor</td>
<td>80%</td>
<td>15%</td>
<td>5%</td>
</tr>
<tr>
<td>Navigational accuracy</td>
<td>94%</td>
<td>5%</td>
<td>1%</td>
</tr>
</tbody>
</table>

Table 10
Distribution of input values of linguistic variables for Scenario 1.

<table>
<thead>
<tr>
<th>Linguistic variable</th>
<th>Favourable values</th>
<th>Poor values</th>
<th>Unfavorable values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteorological conditions</td>
<td>70%</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>Navigational equipment</td>
<td>97%</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>Human factor</td>
<td>80%</td>
<td>15%</td>
<td>5%</td>
</tr>
<tr>
<td>Navigational accuracy</td>
<td>94%</td>
<td>5%</td>
<td>1%</td>
</tr>
</tbody>
</table>

Table 11
Distribution of input values of linguistic variables for Scenario 2.
more so for commercial flights is questionable. It does not seem cost-effective for the airport to invest in additional navigation equipment considering the small traffic volume. On the other hand, even improvement of such a small airport can have a positive impact on the economic development of the immediate area, especially in connection with touristic attractiveness of the region. In this context, Section 3.3 will examine the impact of the introduction of LPV-200 procedures on the PoC for this aerodrome.

3.3. Assessment of LPV-200 implementation for Scenario 3

The results obtained in Scenario 3 show that the PoC at these types of airports is too high. In this section, we will consider whether the implementation of the LPV-200 procedure can change this state of affairs. The introduction of the LPV-200 procedure directly corresponds to a change in the available navigational accuracy. In this case the navigational accuracy coefficient $A$ is equal to 1.2, which is the favourable value. In addition, the availability of LPV-200 procedures is at 99.9%. The set of input data for this case is presented in Table 13. This variant is marked as Scenario 3a.

The obtained result of $1.7 \cdot 10^7$ indicates a significant reduction in PoC, when LPV-200 procedures are implemented in poorly equipped airports such as EPDA. After implementation, the PoC value is then in the same range of values typical for a commercial airport. This clearly shows the potential for improving safety in using this type of procedures. It is worth noting that this improvement takes place at minimum cost, because no investments in infrastructure are necessary.

Of course, the question about the economic viability of transforming airports such as the EPDA for use by civil aircraft (private and commercial) remains valid. This relates to the possible necessity of expanding the operational infrastructure or related to passenger service. However, the analysis carried out under scenarios 3 and 3a shows that from the aspect of safety of air operations, the use of the LPV-200 procedures justifies such a transformation.

3.4. Assessment of LPV-200 implementation for Scenario 2

In this Section, we will check the effects in relation to PoC of LPV-200 implementation in a well-equipped airport that mainly serves commercial passenger traffic. To this end, we will use the results obtained in Scenario 2. The introduction of the LPV-200 procedure corresponds to the change in available navigational accuracy. The set of input data for this case is presented in Table 14. This variant is marked as Scenario 2a.

The obtained result is $6.8 \cdot 10^9$, which indicates an approximately two-fold decrease of the probability of CFIT (from $1.5 \cdot 10^{-5}$) for a well-equipped airport such as EPGD. Although the decrease is not that high, it is important and relevant in the context of air traffic safety. In addition, in the next section we will consider LPV-200 procedures being used as a backup during the occurrence of emergency situations.

3.5. Scenario 4 - EPGD airport, case of navigational equipment failure

In this section, we will analyze the case of failure of the navigation equipment available at the EPGD airport. In contrast to earlier analyzes, in which we used the frequency distribution of individual groups of linguistic variables, we will consider specific values of input linguistic variables here.

Three cases will be considered. The first concerns normal operation with all navigation devices being fully functional. In the second we analyze the case of ILS system failure and the alternative use of the SBAS system instead. The third case concerns failure of the ILS system and the use of LPV-200 procedures for supporting approach for landing. The results are presented in Table 15, considering different values of the input variables Meteorological conditions and Human factor.

In the case of good meteorological conditions, the failure of the ILS system causes an approximate three times increase in PoC, if
SBAS is used instead, and the approach is performed by a pilot for which the Human factor input value is good or average. This is a relatively small increase considering the low absolute values of PoC. However, it is worth noting that for a pilot characterized by the Human factor value at the poor level, this increase is much more significant - almost 50 times greater. This still falls within the limits of the typical commercial airport, however, taking into account the standard conditions characterizing the EPGD airport, it should be considered unacceptable. In this context, the PoC values are important when LPV-200 procedures are available. In every situation, also for a pilot with a Human factor rating of poor, the use of these procedures brings the PoC to the initial value, such as with a fully operable ILS system.

For poor values of the Meteorological conditions input linguistic variable, the increase in PoC in the event of the ILS system failure and the subsequent use of the SBAS system takes on a slightly different character. This is particularly visible for Human factor input variable values at the good and average levels. Loss of navigational accuracy under poor meteorological conditions causes a significant increase in PoC. For a working ILS system, in the case of a pilot with a poor Human factor value, the PoC is also high. Therefore, its increase in the case of failure and use of the SBAS system is relatively small. The use of LPV-200 procedures in the event of failure of the ILS system gives lower PoC values than when using SBAS. However, in contrast to the case of good meteorological conditions, they are slightly worse than with a fully operable ILS system.

For adverse values of the Meteorological conditions input linguistic variable, the nature of PoC changes in case of ILS system failure and the use of the SBAS instead is similar as in the case of poor meteorological conditions. The drop is more significant for pilots with a good or average value of Human factor input variable. In this case, the alternative use of LPV-200 procedures causes, as in the case of favourable meteorological conditions, the return of PoC to the initial value, as in a fully operable ILS system. However, it is worth noting, that for adverse meteorological conditions and the use of the SBAS system, the PoC value goes somewhat beyond the conventional range of values acceptable for typical commercial airports, as specified in Section 3.1. In this context, it seems that introducing the use of LPV-200 procedures at well-equipped airports makes sense and can be recommended.

### 3.6. Scenario 5 - EPCE airport, case of navigational equipment failure

In this section we conducted a similar analysis as in Scenario 4, but with reference to the EPCE airport, which we considered in Section 3.2. As previously, we analyzed three cases. The first concerns normal work with an operating ILS system. In the second, the case of the ILS system failure is considered. In contrast to Scenario 4, the SBAS approach is not available at Cewice airport, and only a non-precision approach using non-directional NDB beacons is possible. The third case concerns the failure of the ILS system and the use of LPV-200 procedures instead. The results are presented in Table 16, considering different values of Meteorological conditions and Human factor input variables.

In the case of good meteorological conditions, the failure of the ILS system causes a significant increase in PoC, if the NDB beacon is used instead, and the approach is performed by a pilot for which the Human factor input variable value is good or average there is an increase of over 20 times. It is obvious that the use of such an inaccurate navigational device as NDB will cause PoC growth. It is worth noting that for a pilot characterized by a Human factor value at a poor level, the PoC level is similar, regardless of the approach

---

### Table 14
Input values of linguistic variables for Scenario 2a.

<table>
<thead>
<tr>
<th>Linguistic variable</th>
<th>Favourable values</th>
<th>Poor values</th>
<th>Unfavorable values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteorological conditions</td>
<td>70%</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>Navigational equipment</td>
<td>97%</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>Human factor</td>
<td>80%</td>
<td>15%</td>
<td>5%</td>
</tr>
<tr>
<td>Navigational accuracy</td>
<td>99.9%</td>
<td>0.1%</td>
<td>0%</td>
</tr>
</tbody>
</table>

### Table 15
Probability of CFIT in case of ILS failure for EPGD Airport.

<table>
<thead>
<tr>
<th>Approach Procedure</th>
<th>Human factor = good</th>
<th>Human factor = average</th>
<th>Human factor = poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILS</td>
<td>3.2·10⁻⁹</td>
<td>3.2·10⁻⁹</td>
<td>3.2·10⁻⁹</td>
</tr>
<tr>
<td>SBAS (ILS failure)</td>
<td>8.2·10⁻⁹</td>
<td>8.2·10⁻⁹</td>
<td>1.5·10⁻⁷</td>
</tr>
<tr>
<td>LPV-200 (ILS failure)</td>
<td>3.2·10⁻⁹</td>
<td>3.2·10⁻⁹</td>
<td>3.2·10⁻⁹</td>
</tr>
<tr>
<td>Poor meteorological conditions</td>
<td>6.6·10⁻⁹</td>
<td>6.6·10⁻⁹</td>
<td>1.0·10⁻⁷</td>
</tr>
<tr>
<td>SBAS (ILS failure)</td>
<td>2.1·10⁻⁷</td>
<td>2.1·10⁻⁷</td>
<td>3.2·10⁻⁷</td>
</tr>
<tr>
<td>LPV-200 (ILS failure)</td>
<td>1.0·10⁻⁸</td>
<td>1.0·10⁻⁸</td>
<td>2.1·10⁻⁷</td>
</tr>
<tr>
<td>Adverse meteorological conditions</td>
<td>1.4·10⁻⁸</td>
<td>1.4·10⁻⁸</td>
<td>3.1·10⁻⁷</td>
</tr>
<tr>
<td>SBAS (ILS failure)</td>
<td>3.2·10⁻⁷</td>
<td>3.2·10⁻⁷</td>
<td>3.2·10⁻⁷</td>
</tr>
<tr>
<td>LPV-200 (ILS failure)</td>
<td>1.4·10⁻⁸</td>
<td>1.4·10⁻⁸</td>
<td>3.2·10⁻⁷</td>
</tr>
</tbody>
</table>
procedure used. However, it is significantly greater than for better trained pilots. The PoC values when the LPV-200 procedures are used are the same as for a fully functional ILS system. This suggests the necessity of introducing the procedures at airports such as EPCE, which are equipped with a navigation system enabling a precision approach, which in case of its failure, navigational accuracy is significantly deteriorated.

For poor values of the Meteorological conditions input linguistic variable, the increase in PoC in the event of the ILS system failure and the use of NDB beacons is of a slightly different nature. It is particularly visible for the Human factor input variable value at the poor level, where the PoC increases by two orders of magnitude to a level clearly unacceptable for commercial air traffic. For the remaining values of the Human factor variable, the increase is much smaller, about four times. Importantly, in all cases, the use of LPV-200 procedures in the event of failure of the ILS system gives the same PoC values as in the case of fully functional ILS.

For adverse values of the Meteorological conditions input linguistic variable, the nature of PoC changes in case of the ILS system failure and the use of NDB beacons or LPV-200 procedures instead has the same character as in the case of poor meteorological conditions.

### 4. Summary and conclusions

The article presents the concept, model and implementation of a hierarchical fuzzy inference system for determining the probability of CFIT accident occurrence. The parameters of the model considered were: the navigation equipment of the airport and corresponding avionic equipment, navigational accuracy of the applied landing approach procedure, meteorological conditions and the condition of the crew performing the operation.

The developed tool was used to assess the baseline level of Probability of Controlled Flight Into Terrain (PoC) and the impact of the implementation of vertical guidance LPV-200 procedures on air traffic safety. Simulation experiments were carried out for a very well equipped airport (EPGD), very poorly equipped (EPDA), and one that only has an ILS navigation system, without any sophisticated backup systems (EPCE). Table 17 summarizes the results obtained.

In summary, the introduction of LPV-200 procedures allows the reduction of PoC, with the highest effect being achieved for the least equipped airport.

In the second part of the paper, the importance of introducing LPV-200 procedures in the event of failure of the main landing approach support system ILS was examined. These calculations were carried out only for EPGD and EPCE airports, because the EPDA airport studied is not equipped with this system. The general result of the conducted simulations indicates that in the case of the ILS system failure, there is an increase in PoC. The scale of this increase varies and depends on the type of backup system used (SBAS or NDB) as well as meteorological conditions and crew condition characterized by the variable Human factor. For a less-equipped aerodrome, in the case of poor or adverse weather conditions, and when the approach is performed by a pilot characterized by Human factor value at a poor level, this increase may be as much as 100-fold. However, in the case when the LPV-200 procedures are implemented at the airport, in most cases the PoC level remains at the same level as with an operating ILS system. Only in the case of a well-equipped airport and poor weather conditions, this level is slightly higher.

In summary, in the event of a failure of the ILS, main approach assistance system the introduction of LPV-200 procedures allows

### Table 16

<table>
<thead>
<tr>
<th>Approach Procedure</th>
<th>Human factor = good</th>
<th>Human factor = average</th>
<th>Human factor = poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILS</td>
<td>1.4·10⁻⁴</td>
<td>1.4·10⁻⁸</td>
<td>3.2·10⁻⁷</td>
</tr>
<tr>
<td>NDB (ILS failure)</td>
<td>3.2·10⁻⁷</td>
<td>3.2·10⁻⁷</td>
<td>3.2·10⁻⁷</td>
</tr>
<tr>
<td>LPV-200 (ILS failure)</td>
<td>1.4·10⁻⁸</td>
<td>1.4·10⁻⁸</td>
<td>3.2·10⁻⁷</td>
</tr>
<tr>
<td>ILS</td>
<td>3.2·10⁻⁷</td>
<td>3.2·10⁻⁷</td>
<td>3.2·10⁻⁷</td>
</tr>
<tr>
<td>NDB (ILS failure)</td>
<td>1.4·10⁻⁶</td>
<td>1.4·10⁻⁶</td>
<td>3.2·10⁻⁷</td>
</tr>
<tr>
<td>LPV-200 (ILS failure)</td>
<td>3.2·10⁻⁷</td>
<td>3.2·10⁻⁷</td>
<td>3.2·10⁻⁷</td>
</tr>
</tbody>
</table>

### Table 17

<table>
<thead>
<tr>
<th>Airport</th>
<th>EPGD</th>
<th>EPCE</th>
<th>EPDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base PoC</td>
<td>1.5·10⁻⁸</td>
<td>3.3·10⁻⁷</td>
<td>1.5·10⁻⁶</td>
</tr>
<tr>
<td>PoC with LPV-200 procedures</td>
<td>6.8·10⁻⁹</td>
<td>1.0·10⁻⁷</td>
<td>1.7·10⁻⁷</td>
</tr>
</tbody>
</table>
maintaining the PoC at the same or close to the basic value level.

The results of our research indicate that the introduction of LPV-200 procedures is clearly positive for the commercial use of small, less equipped aerodromes and thanks to their employment it is possible to keep the PoC at a level similar to typical commercial airports.

References