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Fuzzy risk matrix as a tool for the analysis of the air traffic safety

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ABSTRACT: Air transport has been since years the safest way of traveling. It is a result of wide usage of risk analysis methods, affecting the majority of actions performed in the field of the air traffic management. Risk assessment is usually based on fusing probability of an adverse event with severity of its consequences. They are usually classified into one of the five exclusive categories. That practice seems to be inadequate. Assessments of probabilities and consequences are often imprecise, but are considered to belong to one particular category, that determines further risk assessment. However, there is a whole range of intermediate situations. In classic risk matrix it is difficult to take those situations into account. The aim of this study is to present the risk assessment method that allows expressing the risk using a continuous numeric scale. The fuzzy risk matrix was proposed that is in fact a fuzzy inference system having two inputs and one output. Thanks to applying that mechanism, we are able to compare the risk for different situations, even when they belong to one particular category e.g. *tolerable*. Such comparisons allow rationalization of actions as a part of risk management systems. In this paper the concept of a fuzzy risk matrix is applied to air traffic accident analysis. For the estimation of the accident probability a model based on Petri nets was used. To estimate consequences of a potential accident, an expert knowledge was used. In case of the analyzed incident the system that was created has a hierarchical structure. Experiments conducted by using this tool allow one to conclude that a fuzzy risk matrix is a powerful tool to assess the risk in air transport.

1 INTRODUCTION

Every change of the operating procedure in air transport, implementing a new kind of equipment or software, modification of training programs, are preceded by the risk analysis, in order to check whether the implementation of planned change will at least maintain current safety level. Risk assessment is an important part of this process. A discrete scale that consists of three levels is used in majority of cases. It is said that the risk is acceptable, tolerable or intolerable. A risk matrix is used to make that classification. Each element (meaning each combination of probability and severity of consequences) is tied to one of the three risk assessments (ICAO, 2012).

This practice seems to be inadequate. Assessments of probabilities and consequences are often imprecise. What is more, those assessments often come from experts and have descriptive (qualitative) nature. Their knowledge is subjective and they use linguistic terms that can be understood in different way by different experts. Classic risk matrix was not intended for using such kind of knowledge. In cases where it is appropriate to have more detailed analysis we may use Quantitative Risk Analysis approach. However, the absolute results that are obtained may be questionable if they do not take into account the uncertainty of the knowledge. Possible ways of uncertainty representation are: probabilistic approach, interval representation or fuzzy approach.

In this paper it is proposed to apply fuzzy sets to make the risk assessment. This results in creation of the fuzzy risk matrix which is in fact a fuzzy inference system having two inputs and one output. The concept of a fuzzy risk matrix was proposed by Markowski & Mannan (2008). It was used in the analysis of a distillation column unit. Thanks to applying that mechanism we receive risk assessment that is continuous in the predetermined numerical scale. It allows us to compare the risk for different situations. Such comparisons allow rationalization of actions as a part of risk management systems. This approach provides an improvement that may at some time be considered to replace current practice.

Fuzzy inference systems gain an increasing popularity in risk analysis in many areas of technology. This is caused by high level of uncertainty that is typical for the analysis of consequences of the events, especially in prognostic sense. For that purpose it is proposed to use the holistic approach from the viewpoint of all relevant stakeholders (Wilke et al., 2014). An example of a paper referring to that area in aviation is (Ayres et al., 2013) where the consequences of air traffic accidents in direct proximity of the airport were analyzed. Modeling the consequences of air traffic accidents of the Runway Incursion type is one of the subjects raised in Wilke et al. (2015) paper.

Uncertainty related to risk components is a serious problem for its proper assessment. A general risk-uncertainty framework is presented in (Aven & Zio, 2011). The review of methods for risk analysis under deep uncertainty can be found in (Cox, 2012). Generally a conservative approach is taken. It means replacing uncertain quantities with the values that lead to a higher level of risk. Aven (2015) argues that conservatism should be avoided in risk assessments. Instead, one should try to achieve the best possible estimates of uncertain values. This paper follows that approach.

Fuzzy inference systems for civil aviation safety and security assessment were considered in (Skorupski & Uchroński, 2015a,b). In this kind of systems expert knowledge is used. Opinions of several experts are often taken into consideration to reduce the level of uncertainty. This leads to the need for knowledge aggregation, and verification of the conflicting rules (Skorupski, 2014, 2015b).

The probability of an adverse event occurrence and severity of consequences caused by this particular event are the elements of a risk matrix. Estimation of the probability will be made by simulation and will be exemplified by the model of an air traffic accident created with the use of Petri nets (Skorupski, 2015a). In turn, estimation of consequences will be done using fuzzy inference system.

Structure of the remaining part of the paper is as follows. Section 2 describes the general concept of fuzzy risk matrix. Section 3 presents a serious air traffic incident which will be analyzed using the proposed method. Section 4 includes a description of some of the local fuzzy inference systems used in the risk assessment. Section 5 contains a description of the created computer tool as well as a presentation of simulation experiments performed with this tool. Section 6 includes the summary and the final conclusions.

2 THE FUZZY RISK MATRIX FOR ASSESSING THE RISK OF AN ACCIDENT

The proposed risk assessment method is based on two pillars. The first is a simulation analysis of the probability of an accident. The second is a fuzzy analysis of its effects. Both pillars depend on a number of input parameters, both static and dynamic. The final step of the method is the risk assessment using the fuzzy risk matrix implemented as a fuzzy inference system.

2.1 *Background*

A general concept of risk analysis proposed in this paper is consistent with the International Civil Aviation Organization Safety Management Manual (ICAO, 2012). It involves assigning a probability of an event along with its consequences to one of the five available categories. Combination of the probability and consequences allows a risk assessment and assigning it to one of the three categories: acceptable, tolerable, and intolerable.

Risk Matrix consistent with (ICAO, 2012) is widely used in risk analysis in air traffic. It has, however, quite significant drawbacks. The most important of them is the adoption of discrete values of the probability and consequences. In practice of Safety Management System (SMS) in air traffic, the probability assessment is made by the experts who usually do not want to make very strict evaluations and therefore determine them as located at the intersection of two categories. Unfortunately, a typical Risk Matrix does not facilitate such assessments. Therefore it is proposed to treat both the probability and consequences evaluations as linguistic variables, values of which are represented by fuzzy sets with adequate membership functions.

As it was said above, two estimates are necessary to perform the assessment of risk of an accident. The probability of the event may be obtained using one of the analytic or simulation methods. Here one can point to the Event Tree Analysis, Fault Tree Analysis, Monte Carlo-based methods or Bayesian Belief Networks. Estimation of the consequences of an event by formal methods is very hard. Difficulty arises from the need to anticipate both – actions performed by participants of an event in hazardous conditions and the impact of those actions on the scale of damage or human casualties. The modeling of the consequences of hazardous events may require a different approach for any particular case. Very often the results from a consequences model cannot be used directly in a risk model. This drawback can be removed by the fuzzy risk approach as the consequences are determined by the experts and the consequences modeling is a part of risk assessment.

2.2 *The general structure of the model*

A general structure of the proposed risk assessment model is presented in Figure 1.

Input variables vector $\boldsymbol{X}$ corresponds to measureable parameters typical for particular event, such as: distance, velocity of objects, time necessary to perform an action etc. By using fuzzy inference systems based on the expert knowledge one can transform them into anticipated action y. The same input allows the calculation of the probability y_p of the analyzed adverse event occurrence. Participants' actions allow in turn an assessment of the severity of the consequences y_c. Again, to achieve this, obtaining the expert knowledge is needed. Estimates of the probability y_p and the consequences y_c allow the determination of the risk tolerance level z_r using a fuzzy risk matrix implemented as the fuzzy inference system.

2.3 *Fuzzy risk matrix*

The proposed concept of the fuzzy risk matrix is corresponding to the following fuzzy inference system. Input variables:

1. Linguistic variable *Severity of consequences*, describing outcomes of an event. It will take the following values: *negligible*, *minor*, *major*, *hazardous*,

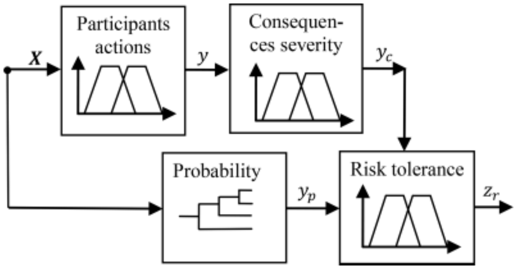

Figure 1. Structure of the model for risk assessment.

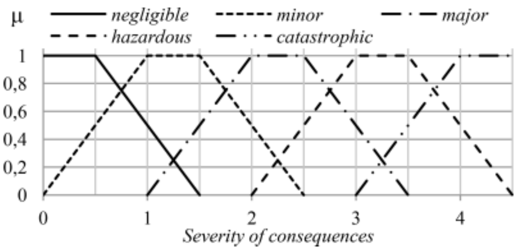

Figure 2. Membership functions of linguistic input variable *Severity of consequences*.

catastrophic. The proposed membership function is presented in Figure 2.

2. Linguistic variable *Probability*, describing the probability of an event occurrence. It will also take five fuzzy values: *very small, small, medium, high, very high*. Scale proposed for that linguistic variable is based on a logarithmic scale, first introduced in (Lower et al., 2013). In this paper however, it was modified by extending its fuzziness to map wider degree of an uncertainty that can be observed while assessing such kind of events (Figure 3).

In turn, linguistic output variable *Risk tolerance* will describe an evaluation of risk in the same way as in (ICAO, 2012) and will take one of the three possible values: *acceptable*, *tolerable*, *intolerable*. In this paper trapezoidal membership functions of fuzzy sets corresponding to the input and output linguistic values were taken. They are presented in Figures 2-4. Model is complemented by fuzzy inference rules representing risk assessment criteria. General principle of creating those rules was adopted in accordance with (ICAO, 2012). Some of the rules are presented in Table 1.

The surface corresponding to the input and output variables and rules base is shown in Figure 5.

3 EXAMPLE

3.1 *Description of the circumstances of serious air traffic incident no. 270/06*

The event took place on 1st September 2006 at Warsaw Chopin airport involving the following aircraft: Airbus A320 and Embraer EMB170. Airbus (A320) crew received instructions from ground controller (GND)

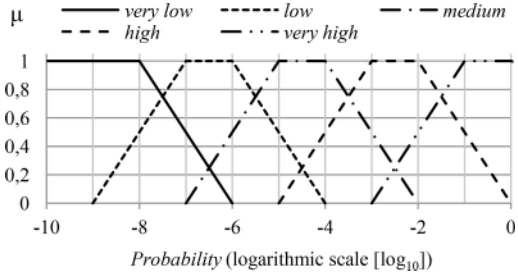

Figure 3. Membership functions of linguistic input variable *Probability*.

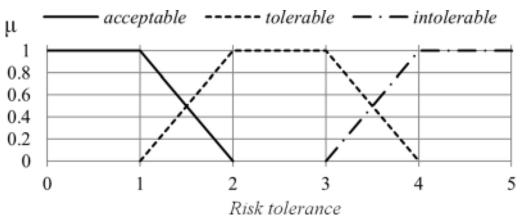

Figure 4. Membership functions of linguistic variable *Risk tolerance*.

Table 1. Fuzzy inference rules for linguistic variable *Risk tolerance*.

Rule	*Probability*	*Severity of consequences*	*Risk tolerance*
3	*very high*	*major*	*intolerable*
11	*medium*	*catastrophic*	*intolerable*
12	*medium*	*hazardous*	*tolerable*
15	*medium*	*negligible*	*acceptable*
16	*small*	*catastrophic*	*tolerable*
24	*very small*	*minor*	*acceptable*

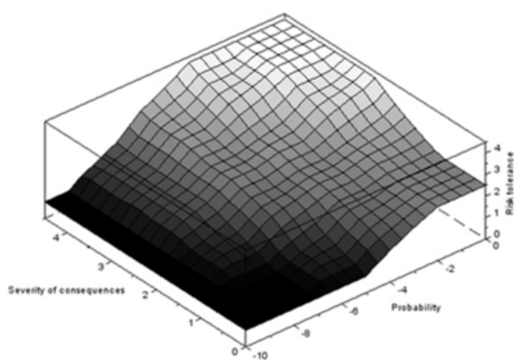

Figure 5. The surface describing *Risk tolerance* in the fuzzy risk matrix.

for taxiing by the taxiway A, and subsequently by the taxiway E to the runway threshold RWY 29 (Figure 6) – green line.

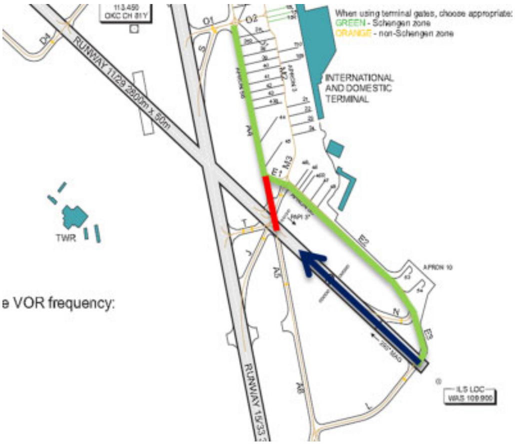

Figure 6. Scheme of the incident no. 270/06.

The A320 pilot acknowledged the taxiing permission properly, but continued taxiing incorrectly - by taxiway A4 straight to the runway – red line. At the same time on runway RWY 29 Embraer (EMB170) began take-off – blue arrow. The airport control tower (TWR) issued the command to the EMB170 crew to stop. Ground controller (GND) proceeded similarly regarding the aircraft A320. Both crews carried out the command.

3.2 *Model for accident probability assessment*

The event has been qualified into a "serious air traffic incident" category as the collision of aircraft almost happened. The most important question is if it is possible to stop the aircraft before the collision point. These are binary events – either the aircraft stops or it does not stop. However, the process that determines this is dynamic. It is required to consider both the response time of individual controllers and crews but also of the dynamic characteristics (speed, accelerations and decelerations) of aircraft movements. For the purpose of determining the probability of an accident occurrence a model in the form of hierarchical Petri net was developed. The model is presented in (Skorupski, 2015a) and will not be described here.

In order to determine the probability of the incident transformation into an accident, simulation method was used. This means that a series of experiments is conducted with the model and the results are being observed.

4 ANALYSIS OF THE INCIDENT NO. 270/06 WITH THE USE OF FUZZY LOGIC

4.1 *Model of severity of the consequences*

Consequences in case of the continuation of the air traffic event no. 270/06 depend on the behavior of both of the crews. Providing that A320 at least partially remained on the runway and EMB170 did not interrupt the takeoff, and then the consequences could even be disastrous. Analysis of the severity of consequences will therefore be based on the following variables:

Input variables:

1. *A320 behavior* – a linguistic variable taking the following values: *braking*, *maneuver*, and *none*. In case of the situation when the distance between the aircraft and the point of collision is large at the moment when the pilot detects the hazard, then *A320 behavior* variable takes the value *braking*. In case of the situation when this distance is insufficient for the total stopping, this variable takes the value *maneuver.* In case of the situation when neither braking nor avoidance maneuvers are possible at the moment when pilot detects the hazard, then variable *A320 behavior* takes the value *none*. Delimitation between particular values of this linguistic variable is not strict; therefore, they are represented by fuzzy sets with trapezoidal membership functions.
2. *EMB170 behavior* – a linguistic variable taking the following values: *braking*, *maneuver*, *none*. The form of membership functions and their sense is similar to variable *A320 behavior*.

Output variable is *Severity of consequences*. It takes fuzzy values described in Section 2.2. Determining those values was based on fuzzy inference rules coming from experts. They are presented in Table 2.

Table 2. Fuzzy inference rules for *Severity of consequences* variable.

Rule	*A320 behavior*	*EMB170 behavior*	*Severity of consequences*
1	*braking*	any	*minor*
2	any	*braking*	*minor*
3	*maneuver*	*maneuver*	*major*
4	*maneuver*	*none*	*hazardous*
5	*none*	*maneuver*	*hazardous*
6	*none*	*none*	*catastrophic*

4.2 *A320 behavior model*

Input linguistic variables:

1. *Taxiing procedure understanding* – a linguistic variable taking the following values: *appropriate*, *not understood*.
2. *A320 recognition of conflict* - a linguistic variable taking the following values: *short*, *average*, *long*. They represent the time after which the A320 crew realizes that their taxiing is incorrect.
3. *GND controller recognition of conflict* - a linguistic variable taking the following values: *short*, *average*, *long*. They represent the time after which the GND controller realizes that the taxiing of the A320 is incorrect and reacts by commanding to stop.

Table 3. Fuzzy inference rules for linguistic variable *A320 behavior*.

Rule	*Taxiing instructions understanding*	*A320 recognition of conflict*	*GND controller recognition of conflict*	*A320 behavior*
1	*appropriate*	*short*	any	*braking*
4	*appropriate*	*average*	*long*	*none*
5	*appropriate*	*long*	*short*	*maneuver*
8	*not understood*	*short*	any	*braking*
11	*not understood*	*average*	*long*	*maneuver*
13	*not understood*	*long*	*long*	*none*

Output variable *A320 behavior* takes fuzzy values defined in the same way as in the *Severity of consequences* model. Model is complemented by the fuzzy rules base obtained from experts – air traffic controllers and aircraft pilots. There are 13 defined rules, 6 of them are presented in Table 3.

4.3 *EMB170 behavior model*

In the analyzed case actions performed by EMB170 crew were correct – an instruction to discontinue the takeoff was properly understood and properly (quickly enough) performed. However, one cannot exclude situation that rejected takeoff procedure will begin after a long time or will not occur at all. Such cases change not only the probability of an accident but can also affect its consequences. Model of EMB170 behavior is similar to model of A320 behavior. It has the following input variables:

1. *TWR controller recognition of conflict* – a linguistic variable representing the time after which TWR controller recognizes the danger and provides the instruction for EMB170 crew. It can take the following values: *short*, *average*, *long*.
2. *EMB170 recognition of conflict* – a linguistic variable describing an ability of the crew to recognize the danger and perform a proper (quick) reaction. It can take the following values: *short*, *average*, *long*.
3. *Braking conditions* – a linguistic variable describing runway surface condition, having impact on the coefficient of friction, and therefore on the effectiveness of braking maneuver. It can take the following values: *good*, *medium*, *poor*.

Output variable *EMB170 behavior* takes fuzzy values as it was described in Section 4.1. Again values of that variable are obtained from a fuzzy inference system based on the fuzzy knowledge base obtained from experts. There are 21 defined rules.

4.4 *Probability of events estimation*

As it was mentioned above, the probabilities of particular traffic situations were estimated by using a model in the form of Petri net described in (Skorupski, 2015a). This model was complemented to take into account different values of coefficient of friction during braking, and also factors that were described in sections 4.2 and 4.3.

5 COMPUTER TOOL AND SIMULATION EXPERIMENTS

The hierarchical fuzzy inference system developed to estimate the severity of consequences and finally the risk of an accident was implemented in SciLab 5.4 environment with Fuzzy Logic Toolbox add-on. FMRE (Fuzzy Matrix Risk Evaluation) software has been created that allows conducting simulation experiments with the following plan. First experiment consists in estimation of the risk for the situation identical to the real serious incident. Next step is an analysis of how the risk will change in the situation when aircraft crews will react within a longer time, due to lower qualifications, worse teamwork abilities or eventually due to lower situational awareness. As a third simulation experiment an analysis of different braking conditions, expressed by the change of the runway coefficient of friction, will be carried out.

Using FMRE software one can assess the severity of consequences and finally the risk by using a fuzzy risk matrix. In case of the risk assessment the results apply to the transformation from the occurred incident into an accident.

5.1 *Nominal situation - as in the incident*

In this section the risk of an event will be assessed, providing that all parameters take values same as in the real incident. Those parameters are presented in Table 4. The source of that data is the report from incident investigation (Civil Aviation Authority, 2008).

Applying the local fuzzy inference system *A*320 *behavior* allows us to estimate this parameter on the level of 0.77, what corresponds to the linguistic variable *braking*. Identical result was obtained for the *EMB170 behavior* model. This is consistent with the course of the real incident. Taking this into account, as a result of applying the local model *Severity of consequences*, we receive the value of 1.25 that corresponds to the linguistic variable *minor*. Consequences that

Table 4. Risk Assessment – parameters as in serious incident.

Input parameter	Value	Output parameter	Value
Taxiing instructions understanding	*not understood*	*A320 behavior*	0.77 (*braking*)
A320 recognition of conflict	15 [sec]		
GND controller recognition of conflict	10 [sec]		
Braking conditions (coefficient of friction)	0.25	*EMB170 behavior*	0.77 (*braking*)
EMB170 recognition of conflict	15 [sec]		
TWR controller recognition of conflict	10 [sec]		
A320 behavior	0.77	*Severity of consequences*	1.25 (*minor*)
EMB170 behavior	0.77		
Probability of an accident	$10^{-3.28}$	*Risk tolerance*	2.36 (*tolerable*)
Severity of consequences	1.25		

Table 5. Risk assessment – pilots and controllers notice the hazardous situation lately.

Input parameter	Value	Output parameter	Value
Taxiing instructions understanding	*not understood*	*A320 behavior*	3.23 (*none*)
A320 recognition of conflict	30 [sec]		
GND controller recognition of conflict	20 [sec]		
Braking conditions (coefficient of friction)	0.25	*EMB170 behavior*	3.23 (*none*)
EMB170 recognition of conflict	30 [sec]		
TWR controller recognition of conflict	20 [sec]		
A320 behavior	3.23	*Severity of consequences*	3.97 (*catastrophic*)
EMB170 behavior	3.23		
Probability of an accident	$10^{-1.95}$	*Risk tolerance*	4.24 (*intolerable*)
Severity of consequences	3.97		

may occur in case of a successful emergency braking (without a collision) are for example: damage of the braking system or tires or minor injuries of passengers, caused for example by being hit by small objects not properly secured for the duration of the takeoff. Probability of an accident received from the Petri net model equals for this example $5.26 \cdot 10^4$. After transformation into the adopted logarithmic scale it gives the value of -3.28, which can be expressed by linguistic variables as a value between *high* and *medium*. Final risk assessment takes the value of 2.36 (in the adopted scale ranging from 0 to 5) which corresponds to the *tolerable* value.

5.2 *Analysis for a less efficient crew*

This section presents an assessment of risk in the circumstances similar to the analyzed incident but in case when the hazard perception ability and resulting crews reaction times vary from the values that took place in the real event. An experiment was conducted consisting in the risk assessment in case when both crews and controllers react significantly slower than in the real incident. In the model for determining the probability of transformation from the incident into an accident twice as long reaction time to the controller's instruction to break the operation was included. Additionally, twice as long time necessary to transmit this instruction by the radio was included. Results of this experiment are presented in Table 5.

Results of this experiment show that this event was properly interpreted as a serious air traffic incident, which means that an accident almost happened. In case of longer reaction times, the crews of both aircraft do not take any action, and therefore the occurrence of an accident depends only on a difference in time between the moments of occupying a collision point by the aircraft. In such situation the severity of consequences can be estimated as *catastrophic*, and the probability of an accident equals $10^{-1.95}$. Obviously in such case the risk is significantly higher and in the adopted scale takes the defuzzified value of 4.24. This can be expressed in the linguistic sense by the *intolerable* value.

5.3 *The case of poor weather conditions*

This section will present the analysis of the influence of weather conditions by adding the question of the runway surface condition. Risk will be assessed for the case of simultaneous occurrence of intense rain, and a snow-water mixture covering the runway. Coefficient of friction for such conditions was derived from (Raymer, 1992). Additionally, a slight increase of a time necessary to notice a hazardous situation by the people related to the A320 aircraft – its crew and the

Table 6. Risk assessment - snow-water mixture covering the runway.

Input parameter	Value	Output parameter	Value
Taxiing instructions understanding	*not understood*	*A320 behavior*	2.4 (*maneuver/none*)
A320 recognition of conflict	18 [sec]		
GND controller recognition of conflict	14 [sec]		
Braking conditions(coefficient of friction)	0.12	*EMB170 behavior*	2.0 (*maneuver*)
EMB170 recognition of conflict	15 [sec]		
TWR controller recognition of conflict	10 [sec]		
A320 behavior	2.4	*Severity of consequences*	2.62 (*major*)
EMB170 behavior	2.0		
Probability of an accident	$10^{-2.99}$	*Risk tolerance*	2.85 (*tolerable*)
Severity of consequences	2.62		

GND controller was taken into consideration. Results are presented in Table 6.

As it is shown, the deterioration of braking conditions by lowering coefficient of friction causes that the taking off EMB170 is not capable of stopping before reaching the collision point and therefore making an avoidance maneuver is necessary. On the other hand, longer reaction time of the A320 aircraft crew causes that their reaction will be either an avoidance maneuver, or there will be no reaction at all. This places the estimation of consequences on the level of *major*. Combined with the calculated probability of an accident, this places a risk assessment on the level of *tolerable*. However, applying a fuzzy risk matrix can clearly indicate the shift towards *intolerable* value.

6 SUMMARY AND FINAL CONCLUSIONS

In this paper the concept of a fuzzy risk matrix applied to air traffic accidents analysis was presented. It allows the expression of both the probability of an event and its consequences in the form of fuzzy linguistic variables. On this basis, a fuzzy inference system can be created, that can be used to assess the risk in the continuous scale, therefore giving a possibility to compare different cases, even when they belong to the same risk category.

For the estimation of the accident probability a model based on Petri nets was used. It takes into account the hybrid nature of an incident. This means incident in which equally important are the static events with constant probability, as well as dynamic events which result in different times of appearing at the collision point by the particular participants of an incident.

To estimate consequences of a potential accident, an expert knowledge was used. Due to its imprecision and subjective nature it is often represented by fuzzy inference systems. In case of the analyzed incident the system that was created has a hierarchic structure.

The developed method and created models were implemented as FMRE software in the SciLab 5.4 environment with the Fuzzy Logic Toolbox add-on. Experiments conducted by using this tool allow one to conclude that a fuzzy risk matrix is a comfortable tool to assess the risk in air transport. Quantitative assessments of risk at the *tolerable* level for the case when a crew has a good situational awareness and very quickly notices the danger were obtained. However, for the case of a barely trained crew that is not well oriented in the traffic situation risk can reach the *intolerable* level. Influence of weather conditions (visibility, runway coefficient of friction) on the risk of the transformation from the incident into an accident was also examined.

Further research should focus on creating an integrated tool to assess the probability and the consequences of the considered events. Further research is also needed in order to determine probabilistic characteristics of the adopted random variables. Yet another important area requiring research is to determine the boundary conditions (for example visibility) at which risk increases up to the level when executing special procedures, such as the low visibility procedures (LVP), is necessary.

Generally, the fuzzy risk matrix approach provides an improvement to the classic risk methods that may at some time be considered to replace current practice. This may be particularly important in high risk industry where rough risk assessments are insufficient.

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