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Falavigna, Gabriela Pasetto; Iescheck, Andrea Lopes; Souza, Sergio Florencio de

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ORIGINAL ARTICLE

OBSTACLES RISK CLASSIFICATION MODEL IN AERODROMES PROTECTION ZONES USING THE MULTI-CRITERIA DECISION ANALYSIS AHP

Modelo de classificação do risco de obstáculos em zonas de proteção de aeródromos usando o método de decisão multicritério AHP

Gabriela Pasetto Falavigna[1] - ORCID: 0000-0003-3028-0448
Andrea Lopes Iescheck[1] - ORCID: 0000-0002-8390-435X
Sergio Florencio de Souza[1] - ORCID: 0000-0002-4720-6714

[1]Universidade Federal do Rio Grande do Sul - UFRGS, Programa de Pós-Graduação em Sensoriamento Remoto, Porto Alegre - Rio Grande do Sul, Brasil.
E-mail: gabi_falavigna@hotmail.com; andrea.iescheck@ufrgs.br; sergio.florencio@ufrgs.br

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Abstract:

Aerodromes protection zones are defined by plans that establish the limits that objects can project into airspace without affecting the safety and regularity of air operations. These plans are composed of a set of imaginary three-dimensional surfaces that impose restrictions on the use of properties within the protection zones. Our research problem is how to classify the risk of obstacles in aerodromes protection zones. In this paper, we propose a methodology to obtain an obstacle risk classification model. We defined the risk factors and applied a questionnaire to an expert in civil aviation. The obstacle risk classification model resulted from the specialist analysis and by applying the analytic hierarchy process (AHP) for multi-criteria decision analysis. The advantage of the AHP in studies that use specialists' empiric knowledge for risk modeling is the treatment of uncertainties, and the use of tangibles and intangibles criteria. The results showed that the most significant influence on the risk of an obstacle is how much that obstacle protrudes the limiting surfaces, followed by the distance between the obstacle and the nearest airport runway threshold, the limiting surface in which the obstacle is, and the nature of the obstacle.

Keywords: Aerodrome protection zone; Analytic Hierarchy Process; Risk modeling.

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1. Introduction

Obstacles in aerodromes protection zones pose complex problems for air safety and the economy of cities. These violations can reduce or cancel landing procedures (Santos and Müller 2014), in addition to preventing the expansion of aerodromes and limiting the size of aircraft allowed to operate at airports.

Aerodrome Protection Zone Basic Plan (PBZPA) consists of a set of three-dimensional (3D) imaginary surfaces, imposing altimetric restrictions on the use of properties within the protection zone (DECEA 2019). Such surfaces establish the limits that objects can protrude into the airspace without adversely affecting the safety and regularity of air operations (Brasil 2015). The configuration of the limiting surfaces depends on the characteristics of the aerodrome, such as location and height. The establishment of this configuration is according to the type of runway threshold operation, the aerodrome reference code, the performance categories of the aircraft in operation or planned to operate at the airport, and the type of runway threshold use (landing, takeoff, or landing and takeoff) (Brasil 2015). The Federal Aviation Administration (FAA), a U.S. government agency responsible for civil aviation regulations, establishes the imaginary surfaces for obstruction evaluation through the Federal Regulation Title 14 Part 77, Safe, Efficient Use and Preservation of the Navigable Airspace. This regulation defines the object identification surfaces (OIS), and the standards and notification requirements for objects that affect navigable airspace, allowing to previously identify potential risks and then preventing or minimizing them (FAA 2021a, 2021b).

Medeiros and Correia (2010) evaluated non-conformities in the infrastructure of Brazilian airports in terms of air safety. They observed that eight of the twenty largest Brazilian airports in passenger movement had irregularities. These inadequacies mainly refer to the absence of runway end safety area and the obstacles in the runway strip, and obstacles that violate the limiting surfaces. According to their study, all eight airports had obstacles on the runway strip. Six had obstacles that violated the transition surface, and two had obstacles that violated the approach and takeoff surface.

The safety of the aircraft in the vicinity of an aerodrome during the approach, takeoff, and taxiing is a prerequisite in air transport (Audu 2016). The correct identification of obstacles around airports is essential to ensure the safety and regularity of air operations. In this context, there are several works concerning methodological proposals to identify obstacles to airports (Parrish and Nowak 2009, Pinelli and Veracini 2015, Audu 2016, Falavigna, Iescheck and Souza 2020). Falavigna, Iescheck and Souza (2020) identified and quantified Salgado Filho International Airport obstacles in Porto Alegre city (Brazil), using 3D models of urban plots, buildings, and PBZPA. This study showed that 4.52% of the urban plots and 13.17% of the buildings in the study area exceeded the limit imposed by the airport's PBZPA.

In addition to identifying and quantifying obstacles, it is necessary to assess the risk that these obstacles pose to air safety. Knowledge of the risk level of each obstacle is vital for mitigating risks to air operations. To ensure an acceptable level of operational safety at airports and improve the airport structure, it is necessary to know the areas that present the highest risks (Barroso and Correia 2014).

There are several studies on runway excursions (Fortes and Correia 2012, Barroso and Correia 2014, Correia and Neto 2014). However, few studies have considered airports' PBZPA in assessing the risk of obstacles that violate the aerodrome protection zone. Besides, there is no standardization on how to classify the risk of these obstacles. The International Civil Aviation Organization (ICAO) guideline on safety risk classifies the risk of obstacles into three categories: intolerable, tolerable, and acceptable. The definition of these categories is following the probability of an accident occurring and the possible economic, social, and environmental impacts related to that accident (ICAO 2018).

We must consider several factors when modeling the risk of obstacles to airports. The Analytic Hierarchy Process (AHP), developed by Saaty in 1980, is a multi-criteria decision analysis used in complex decision-making scenarios. The base of this method is decomposing the problem into hierarchy levels for its better understanding and evaluation. In general, the steps involved in the method consist of: defining the criteria or factors relevant to the study; organizing the factors in a reciprocal matrix, called “pairwise comparison matrix”; performing pairwise comparisons (judgments) to establish the relative importance of the factors, and obtaining the relevance (weight) of each factor to the analysis. It is necessary to calculate the consistency index and the inconsistency ratio for the matrix to assess the consistency of the results. Inconsistency ratio values up to 0.10 (10%) are considered acceptable (Saaty 1984).

The AHP has been used for evaluating airport safety risks. Barroso and Correia (2014) applied a questionnaire to an expert and used the AHP to assess the risk of obstacles to Rio de Janeiro International Airport. They rank the obstacles most likely to cause a severe event, considering ten risk factors selected from the ICAO safety risk severity table (ICAO 2009). The inconsistency ratio obtained for the pairwise comparison matrix was 17%, which exceeded the value considered tolerable by the method. However, the authors did not revise the matrix as recommended in the AHP. In the USA, Wang, Hu and Tao (2004) used empiric knowledge and the AHP to model the risk of obstacles that violate the limiting surfaces of Santa Barbara Airport, California. The authors considered four risk factors and analyzed the protruding condition of the obstacles above the limiting surfaces. They mapped the obstacles risk, classifying the obstacles as high, medium, and low risk. Ozdemir, Basligil and Ak (2016) implemented the fuzzy ANP (Analytic Network Process) and the fuzzy AHP methods for prioritizing and evaluating airport safety risk criteria. In this study, the authors considered three main risk criteria (human factors, facility and equipment factors, and environmental factors), 14 subcriteria and five aviation sector experts’ evaluations. Both of the methodologies produced the same results and considered the subcriteria “safety conscious”, “flight volume condition” and “airport geographic environment condition” the most important risk factors for airport safety.

These reviews show that AHP is applied in studies that use specialists’ empiric knowledge for modeling airports obstacles risk and for evaluating airport safety risk criteria. The innovation of our work about the others is that we considered how much the obstacle protrudes each limiting surface in obstacle risk modeling. Also, we prepared a general questionnaire, adaptable to any airport, and we implemented methods to improve the consistency of the pairwise comparison matrix of the AHP.

In this context, our research problem is: Considering the obstacles that violate the aerodrome protection zone, how to classify the risk that these obstacles pose to the security and maintenance of air operations at airports?

This study aims to propose a methodology to obtain a risk classification model for obstacles in aerodrome protection zones to map obstacles risk in the Porto Alegre International Airport protection zone, assisting in the effective management of obstacles and approaches to risk mitigation actions for airspace operations. Also, the specific objectives comprise defining the risk factors to obstacles and getting the relevance (weight) of each risk factor for the analysis.

2. Materials and Methods

The Porto Alegre International Airport (Figure 1) is located in the northern zone of Porto Alegre, the capital city of the state of Rio Grande do Sul. This region extends to 127.57 km², which represents 27.04% of the area of the municipality (OBSERVAPOA 2021). Porto Alegre’s Airport has the largest passenger traffic of Brazil’s southern region, with 82,461 passenger movements in 2019 (CGNA 2020).

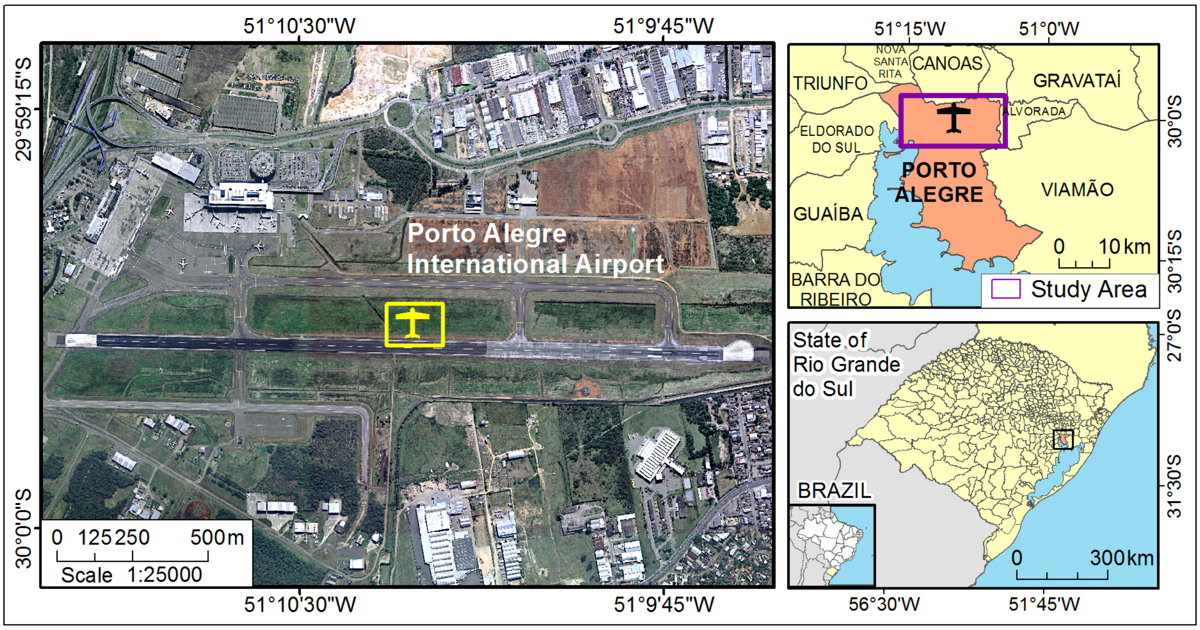

Figure 1: Location of Porto Alegre International Airport.

In this work, we divided the methodology into three steps. The first step consisted of risk modeling using the AHP. In this step, we defined the risk factors and prepared a questionnaire that an expert in civil aviation answered. Based on the expert's answers, we established the relative importance between the risk factors and built the AHP's pairwise comparison matrix. The second step included the analysis and improvement of the comparison matrix consistency. In this stage, we calculated the consistency index and the inconsistency ratio of the matrix. Finally, in the third step, we defined the weights of each risk factor using the AHP and developed a model for obstacle risk' classification. We used the free and open-source software Scilab to implement the AHP and the methods for consistency improvement of the pairwise comparison matrix. Figure 2 illustrates the steps of the research method.

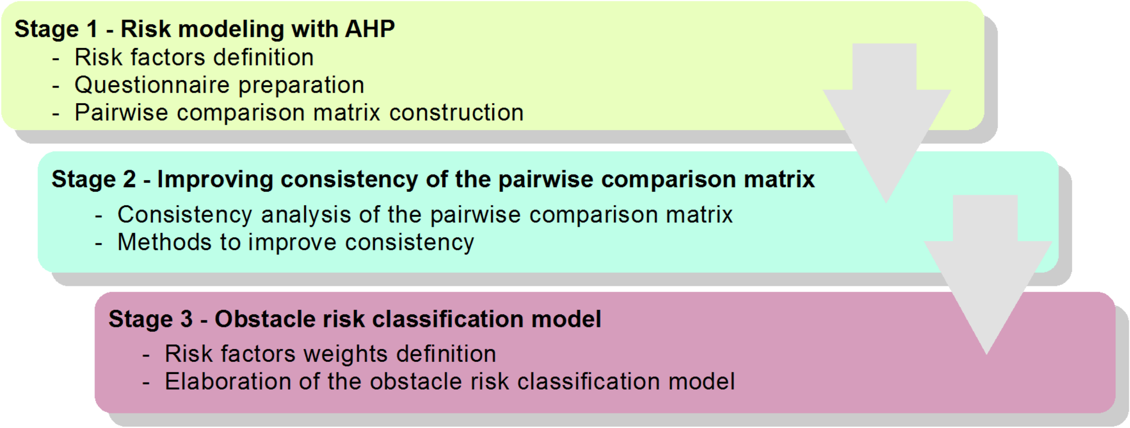

Figure 2: Methodology's flowchart.

2.1 Risk modeling using the Analytical Hierarchy Process (AHP)

The AHP is a multi-criteria decision analysis developed by Thomas L. Saaty in 1980, used in complex decision-making scenarios in engineering, industry, environment, education, politics, and economics. The AHP is widely used in resource allocation and planning issues and assessing environmental impacts (Saaty 1984, Saaty and Vargas 2012). Civil aviation used it in studies on the assessment and classification of the risk of obstacles to airports (Wang, Hu and Tao 2004, Barroso and Correia 2014) and studies on prioritizing research and development projects (Silva, Belderrain and Pantoja 2010).

Saaty (2008) defines the AHP as a process to obtain measurements through pairwise comparisons between the elements analyzed. Such comparisons are made through judgments of specialists, using a priority scale, which represents how important an element is related to another. The AHP facilitates the understanding and assessment of the problem by dividing it into hierarchy levels and determining a global action for each alternative, prioritizing or classifying these alternatives (Silva, Belderrain and Pantoja 2010).

In this study, we chose to use the AHP because it is one of the most widely employed decision support tools (Ozdemir, Basligil and Ak 2016), because of the well-known contribution of the AHP on the treatment of uncertainties in studies that use specialists' empiric knowledge (Silva Junior 2015), and because this method is admittedly functional for manipulating intangible criteria together with tangibles (Souza 2006). Also, we considered few factors (less than 7) to be compared simultaneously. According to Saaty (1977), the human mind is limited to 7 ± 2 factors for simultaneous comparison; i.e., there is a psychological limit that establishes that an individual cannot simultaneously compare (judge) more than seven elements (plus or minus two) without being confused.

To assess the risk that an obstacle poses to compromising the safety and regularity of air operations at an airport, we defined risk factors for the obstacles. We used the risk factors based on Wang, Hu and Tao (2004): distance, location, type, and protrusion. However, we adopted a different meaning for the protrusion factor. While Wang, Hu and Tao (2004) assessed which limiting surface the obstacle protrudes, we analyzed how much each obstacle protrudes the limiting surfaces. We changed the definition of this factor, considering that obstacles protruding more or less the same limiting surface will have different associated risk levels. Thus, we defined the risk factors (Figure 3) as follows: **(a) Distance**: distance between the obstacle and the nearest airport runway threshold; **(b) Location**: in which PBZPA's limiting surface the obstacle is; **(c) Type**: nature of the obstacle (relief, building, pole, antenna or tower); **(d) Protrusion**: how much the obstacle protrudes each limiting surface of the PBZPA (0.5m, 1m, 2m, for example).

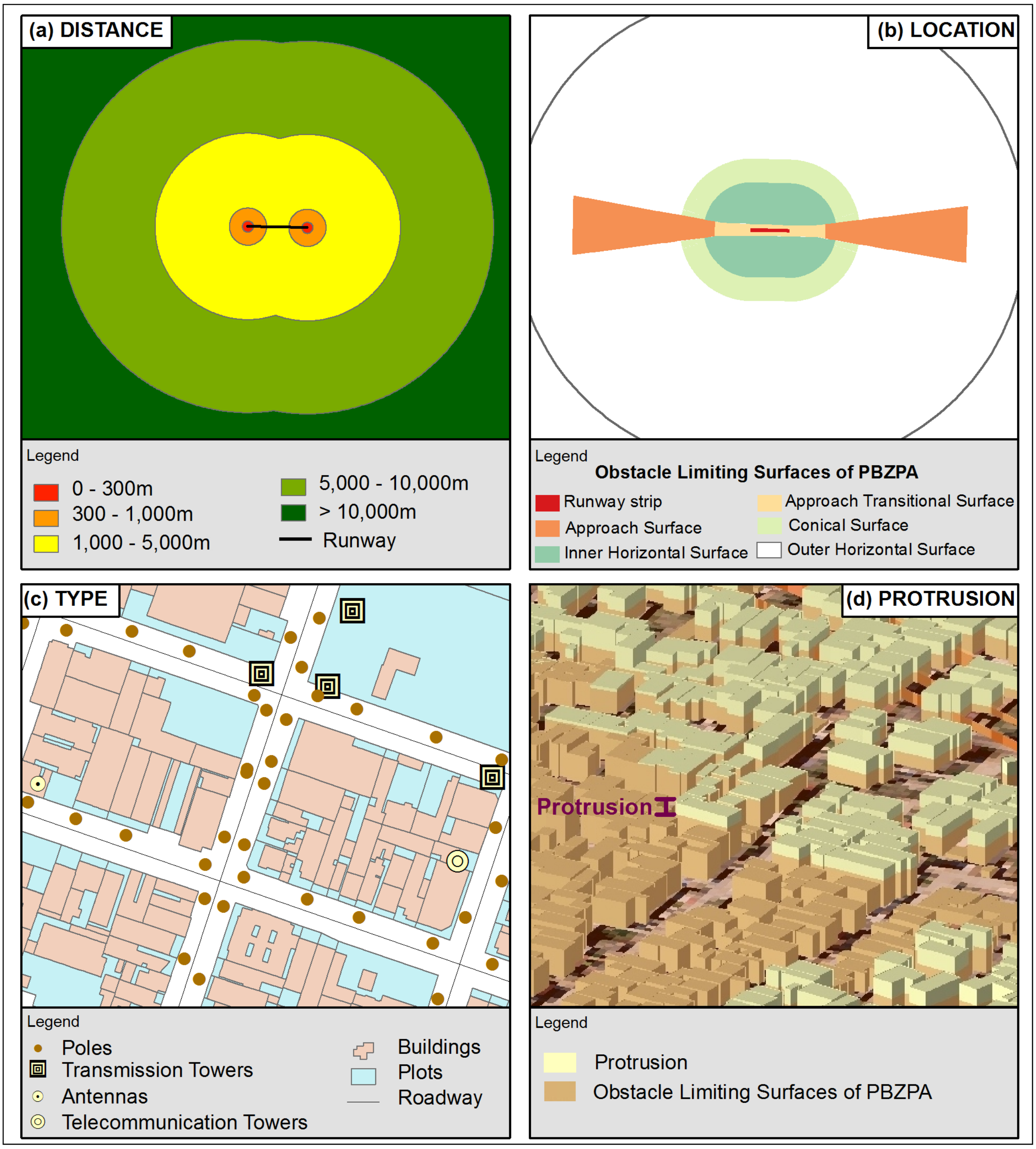

Figure 3: Risk factors: (a) Distance; (b) Location; (c) Type; (d) Protrusion.

We prepared a questionnaire to obtain an expert opinion about the relevance of the risk factors in the analysis and the relative importance in modeling the risk of airport obstacles. The questions were chosen based on the Barroso and Correia (2014) questionnaire. The questionnaire begins with questions about the specialist's level of education, position/occupation, and experience in aviation and airports. We collected this information to verify the specialist's level of knowledge and interpret the answers. The participation of specialists with a high level of knowledge is essential to preserve the accuracy of their information (Barroso and Correia 2014).

Next, to verify the relevance of these factors in risk modeling, we asked the expert about the importance of these factors in assessing the risk of airport obstacles to point out the relevance of each factor in the analysis. The expert understood that all the risk factors are essential, pointing to the protrusion as highly relevant and the others as very relevant to study the risk of airport obstacles.

From this, we divided each risk factor into classes and asked the expert about the likelihood or the dangerousness of each class, considering the safety and regularity of air operations. For the assessment of the classes, the expert used a scale from 1 to 5, in which number 1 represents “very unlikely/very little dangerous” and number 5 “extremely likely/dangerous.”

Lastly, we asked the expert to compare the risk factors to determine their relative importance. We organized the factors in pairs (i, j), as proposed by the AHP, and the expert compared the factors using Saaty’s fundamental scale (Table 1). To simplify the expert’s judgments and avoid inconsistency, we did not use the fundamental scale’s intermediate values (Barroso and Correia 2014).

Table 1: Saaty’s fundamental scale.

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective.
3	Moderate importance	Experience and judgment slightly favor one activity over another.
5	Strong importance	Experience and judgment strongly favor one activity over another.
7	Very strong importance	An activity is very strongly favored over another; its dominance is demonstrated in practice.
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation.
Reciprocals of the above non-zero numbers	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption.
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When intermediate values are needed.
1.1 – 1.9	If the activities are very close	It may be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

Source: Adapted from Saaty (1984, 2008).

We organized the comparison results in a reciprocal matrix A_{nxn} in which we associated the rows and columns with the risk factors. After constructing the pairwise comparison matrix A_{nxn}, we extracted the relative importance of the factors to obtain the weight of each factor in the risk classification model. Thus, we calculated the priority vector, which is a normalized principal eigenvector of the matrix A_{nxn}, given by expression (1):

$$w = (w_1, \dots w_n)^T \tag{1}$$

As the AHP allows inconsistencies in judgments, there is a particular concern with measuring these inconsistencies. The consistency index of a pairwise comparison matrix is used as a measure of the consistency deviation and represents the variance of the error incurred in estimating a_{ij} (Saaty and Vargas 2012). Expression (2) defines the consistency index ($C.I.$):

$$C.I. = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

where λ_{max} is the largest eigenvalue of the matrix A_{nxn} and n is the number of factors assessed.

Through simulations of random reciprocal matrices of different orders, we established the average consistency indices, known as random indices ($R.I.$), using Saaty's fundamental scale, according to Table 2 (Saaty 1984, Saaty and Vargas 2012).

Table 2: Average random consistency index ($R.I.$).

n	1	2	3	4	5	6	7	8	9	10
$R.I.$	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

Source: Adapted from Saaty and Vargas (2012).

The ratio between $C.I.$ and $R.I.$ is called the inconsistency/consistency ratio ($C.R.$) (Saaty 1984, Saaty and Vargas 2012). According to Saaty (1984), the idea of consistency is a central concern in all analyzes. Inconsistency allows us to readjust a judgment system to receive new data, but we must admit it without dominating or confusing consistency. Values of the order of 0.10 for $C.R.$ are considered acceptable; for values higher than this, revisions in the judgments are recommended (Saaty and Vargas 2012). An inconsistency of up to 10% means that the adjustment is minor compared to the eigenvalue entries' actual values (Saaty and Vargas 2012). Thus, the pairwise comparison matrix will be entirely consistent when it has a $C.R.$ equal to zero, that is when the specialist's judgments are entirely consistent (Vasconcelos and Mota 2014).

2.2 Improving the consistency of the pairwise comparison matrix

The AHP allows for inconsistency since, in making judgments, individuals tend to be more cardinally inconsistent than consistent. This fact occurs because individuals are unable to estimate measurement values accurately, even using a known scale. Such estimates become even more complicated when individuals deal with intangible and ordinarily intransitive comparisons (Saaty and Vargas 2012). When dealing with objective comparisons, a pairwise comparison matrix can be perfectly consistent but irrelevant and deviated from true values. For many reasons, a minimum of inconsistency can be considered good, and forced consistency, without knowledge of the exact values, is an undesirable compulsion (Saaty and Vargas 2012).

Considering that judgments can be inconsistent, Saaty and Vargas (2012) proposed methods to improve a pairwise comparison matrix's consistency. We used two methods to identify where the inconsistency is.

According to the first method proposed by Harker, for positive reciprocal matrices, to identify an entry of A whose adjustment would result in the highest rate of variation of λ_{max}, we must examine the values resulting from expression (3):

$$\frac{\partial \lambda_{max}}{\partial a_{ij}} = v_i w_j - {a_{ji}}^2 v_j w_i, i > j \tag{3}$$

with v being the eigenvector of the matrix A^T; i.e., we must evaluate all elements of the upper triangle of the matrix, the $\frac{n(n-1)}{2}$ comparisons, and then select the highest absolute value. Thus, we change the matrix entry associated with this highest absolute value (Saaty and Vargas 2012).

The idea of Harker's method is to find the element that causes the largest variation in the λ_{max}, based on the analysis of the partial derivative matrix and modifying the value of the element of the original matrix, that is, reviewing this judgment in the pairwise comparison matrix (Wolff 2008). We can repeat the process until achieving the desired $C.R.$ If the judgments indicated cannot be changed completely, we can partially change them according to the specialist's understanding (Saaty and Vargas 2012).

Another method used to improve the consistency of a pairwise comparison matrix suggests the analysis of a disturbance matrix, defined by expression (4):

$$\gamma_{ij} = a_{ij} \times \frac{w_j}{w_i} \tag{4}$$

Thus, we analyze the entry a_{ij} that has the highest value of γ_{ij} and see if that entry can be reasonably smaller. Such a change in a_{ij} is also expected to result in a new pairwise comparison matrix with a lower associated principal eigenvalue (Saaty and Vargas 2012).

Harker demonstrated that when calculating the new eigenvector w, after changing the entry i,j, it is desired for the new entry i,j to be equal to w_i/w_j and the value of the reciprocal entry to a_{ij} to be equal to w_j/w_i (Saaty and Vargas 2012). The eigenvector of the last matrix is then taken as the priority vector w and the known values of w_i/w_j and w_j/w_i are used to replace the values of the entry a_{ij} and its reciprocal in the matrix. Saaty and Vargas (2012) suggest that the divisions' values should be rounded to the nearest integer of Saaty's fundamental scale. The specialist is then asked to change his judgment to the suggested value of a_{ij} as much as possible. If the specialist does not want to change the original value of that entry, we considered the second most inconsistent judgment and repeated the process.

In summary, this method finds the element of the pairwise comparison matrix that causes the greatest disturbance in the consistency of the matrix and suggests changes for this judgment and its reciprocal. Also, it suggests new values for the entry and in its reciprocal that will result in a matrix consistent with $C.R. < 0.10$. The elements that have some disturbance are those with $\gamma_{ij} > 1$. Therefore, it is desired to find the element whose value is the farthest from one and verify whether it and its reciprocal can be changed in the original matrix (Wolff 2008).

2.3 Obstacle risk classification model

We developed the obstacle risk classification model present in aerodrome protection zones according to the risk factors and their respective weights. Thus, the risk of obstacles ($R.I.$) is given by expression (5):

$$RI = (w_1F_1) + (w_2F_2) + \ldots + (w_nF_n) \tag{5}$$

With $w_1 + w_2 + \ldots + w_n = 1$, w_i representing the weights of each risk factor and F_i representing the risk factors considered in the analysis.

Expression (5) shows that the greater the weight of a risk factor, the greater the influence of this factor in obstacle risk modeling. The values obtained for $R.I.$ vary according to the risk scale adopted to assess the classes of risk factors.

In this study, we adopted a scale of 1 to 5 to analyze the factors' classes, in which number 1 means "very unlikely/very little dangerous" and number 5 means "extremely likely/dangerous." So, values of RI close to 1 represent obstacles that are less dangerous and less likely to compromise air safety. On the other hand, values of RI close to 5 represent more dangerous obstacles, with a high probability of compromising the safety and maintenance of the airport's air operations.

3. Results

3.1 Questionnaire results

We organized the results of the expert's judgments in the pairwise comparison matrix presented in Table 3. The comparisons made for each pair of risk factors provided the a_{ij} entries for the matrix. According to the AHP, comparisons give a unit diagonal when comparing a risk factor to itself. As the pairwise comparison matrix is reciprocal, the values below the unit diagonal are reciprocal and obtained indirectly: $a_{ji}=1/a_{ij}$. We present the questionnaire with the expert's answers in Appendix.

Table 3: Pairwise comparison matrix.

Risk factors (F_i)	Distance	Location	Type	Protrusion
Distance	1	3	5	1/3
Location	1/3	1	9	1/3
Type	1/5	1/9	1	1/3
Protrusion	3	3	3	1

Table 3 shows that the expert considered moderately more important the distance between the obstacle and the nearest runway threshold than the obstacle location. Furthermore, he/she considered the distance strongly more important than the nature of the obstacle. The obstacle location was considered highly more important than the nature of the obstacle. On the other hand, how much each obstacle protrudes the limiting surfaces is moderately more important than the distance, location, and type of the obstacle in risk modeling.

After calculating the principal eigenvalue, we evaluated the consistency of the results by calculating the consistency index ($C.I.$) and the inconsistency ratio ($C.R.$) of the matrix. Thus, for this pairwise comparison matrix, were obtained $C.I. = 0.255$ and $C.R. = 0.287$. This fact means that the matrix is inconsistent and the judgments matrix should be reviewed when values are greater than 0.10. Before interviewing the expert again, we improved the pairwise comparison matrix's consistency to identify which judgment was causing the largest perturbation in the matrix consistency.

3.2 Consistency of the pairwise comparison matrix

Initially, we implemented Harker's method, which consists of finding the entry that results in the largest rate of change in λ_{max} of the pairwise comparison matrix, based on the analysis of the partial derivatives of the judgments matrix. For this method, in addition to the priority vector w, the eigenvector of the matrix A^T, called v, was calculated. We replaced the values of n, A, w and v in expression (3) and obtained the matrix of the partial derivatives for the judgments matrix, as shown in Table 4.

Table 4: Partial derivatives matrix.

Risk factors (F_i)	**Distance**	**Location**	**Type**	**Protrusion**
Distance	0	0.0182703	-0.0003432	-0.159285
Location	0	0	0.0089113	-0.0761709
Type	0	0	0	**0.2354559**
Protrusion	0	0	0	0

Looking at Table 4, we noted that the (3, 4) entry of the matrix of the partial derivatives, in bold, has the largest absolute value. Therefore, according to Harker's method, we must review the relative importance between the factors type and protrusion.

After, we used another method to improve the matrix consistency based on the analysis of the perturbation matrix. The entries that have some perturbation about ones of a consistent matrix are those with $\gamma_{ij} > 1$. We used the expression (4) to obtain the perturbation matrix, shown in Table 5.

Table 5: Perturbation matrix.

Risk factors (F_i)	**Distance**	**Location**	**Type**	**Protrusion**
Distance	1	2.1929501	1.0579215	0.5157343
Location	0	1	**2.6050642**	0.7055349
Type	0	0	1	2.4374884
Protrusion	0	0	0	1

Table 5 shows that the (2, 3) entry of the perturbation matrix, in bold, is the one with the largest perturbation. Thereby, the expert must review the judgment related to this entry in the pairwise comparison matrix by rethinking the relative importance between location and type. Besides identifying the judgment that should be reviewed, this method suggests the most consistent value for the identified position. The method suggested changing the value of the entry (2, 3) and its reciprocal entry (3, 2) to 1, considering the factors location and type of equal importance in the risk modeling of obstacles to airports.

3.3 Modified pairwise comparison matrix

Considering the methods for reviewing the judgments, we noted that the expert initially assessed the location factor as hugely more important than the type factor. Also, Wang, Hu and Tao (2004) considered the location factor strongly more important than the type factor. Therefore, we understood that the answer of the second method to consider location and type factors of equal importance did mathematician sense, but it might not match reality.

We interviewed the expert again and suggested a reassessment of the judgments identified by both methods. We proposed changes in the values of the entries (3, 4) and (2, 3) and their reciprocals entries in the pairwise comparison matrix of Table 3. To avoid the new values return another inconsistent matrix, we suggested that the expert change these values to 1/9 and 3, respectively. We recommended the value 3, moderately more important on Saaty's fundamental scale, because it is between the one suggested by the method and the value adopted by Wang, Hu and Tao (2004), and the value 1/9, which means extremely less important on the Saaty's fundamental scale, because it was the value adopted by Wang, Hu and Tao (2004).

We obtained a new pairwise comparison matrix (Table 6) with the expert's acquiescence for the suggested changes. After calculating the principal eigenvalue of the last matrix, we evaluated its consistency by recalculating the indexes *C.I.* and *C.R.* This time, the matrix was consistent with *C.I. = 0.038* and *C.R. = 0.043*, matching a 4.3% inconsistency in the judgments. According to AHP, this means that the adjustment is smaller than the eigenvalue entries' actual values.

Table 6: Modified pairwise comparison matrix.

Risk factors (F_i)	**Distance**	**Location**	**Type**	**Protrusion**
Distance	1	3	5	1/3
Location	1/3	1	3	1/3
Type	1/5	1/3	1	1/9
Protrusion	3	3	9	1

After normalizing the principal eigenvector of the consistent matrix, we obtained the priority vector w with the weights of each risk factor. Figure 4 shows that the protrusion factor had the highest weight (0.54 or 54%), followed by distance (27%), location (14%), and type (5%).

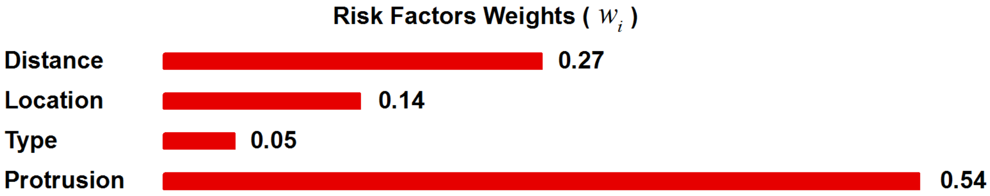

Figure 4: Risk factors weights.

3.4 Obstacle risk classification model

In this paper, we modeled obstacles risk (*RI*) from the definition of the risk factors and their weights. Initially, we divided the risk factors into classes, and the expert assigned risk scores to each class, as summarized in Table 7.

Table 7: Classes of the risk factors and risk scores.

Risk scores	**Extremely likely or dangerous**	**Very likely or dangerous**	**Likely or Dangerous**	**Unlikely or Little dangerous**	**Very unlikely or Very little dangerous**
	5	4	3	2	1
Distance	0 to 300m	300 to 1,000m	1,000 to 5,000m	5,000 to 10,000m	> 10,000m
Location	Approach Surface	Inner Horizontal Surface	Transitional Surface	Conical Surface	Outer Horizontal Surface
Type	Poles, Antennas, and Towers	Relief and Buildings	N/A		
Protrusion	> 4.5m	3.1 to 4.5m	0 to 3.0m	N/A	

Table 7 indicates that any obstacle type had a risk score of more than three; relief and buildings are considered very dangerous obstacles; poles, antennas, and towers are considered extremely dangerous. Any obstacles that protrude the limiting surfaces had not a risk score of less than three and probably will compromise the safety and regularity of air operations at the airport. Obstacles inserted in the approach surface and inner horizontal surface within a radius of approximately 1km from the runway thresholds of the airports are very or extremely dangerous to airspace safety.

Based on the expert's analysis, with the risk factors definition and the risk scores assignment to the classes, and the AHP, with the determination of the weight of each risk factor, we replaced the F_i and w_i values in expression (5), as follows:

$$RI = (0.27 \times Distance) + (0.14 \times Location) + (0.05 \times Type) + (0.54 \times Protrusion) \tag{6}$$

In expression (6) the protrusion factor has the most significant influence in modeling obstacles risk. Therefore, the more an obstacle protrudes the limiting surfaces, the more dangerous the obstacle will be, and more significant will be the likelihood of that obstacle compromising the safety of air operations. The distance and location factors influence the risk assigned to obstacles, but with less intensity when compared to the protrusion factor. On the other hand, the type factor does not significantly influence risk modeling because any obstacle that protrudes the limiting surfaces will most likely compromise airspace safety. However, learning the nature of the obstacle that poses risk is essential for adopting proper risk mitigation actions. So, despite the type having the lowest weight among the considered factors, this risk factor improves the proposed model and is relevant for the analysis, confirming what was pointed out by the expert, who considered this factor very relevant in analyzing the obstacles risk. Finally, considering the risk scores assigned to classes of the risk factors (Table 7), RI values between 4 and 5 signal very or extremely dangerous obstacles, with a high probability of compromising the safety and maintenance of air operations at airports.

4. Discussion

The inconsistent result obtained for the first pairwise comparison matrix indicates the need to make adjustments to the questionnaire for future researches. In this work, we were concerned to prepare an impartial questionnaire, not to influence the expert's statements. It is possible to make the questionnaire clearer to the interviewee to minimize inconsistencies in future researches. Also, the questionnaire could be applied to a more significant number of specialists to get redundancy of information, assisting in resolving inconsistencies. However, we emphasize that specialists with a high level of knowledge are essential for maintaining the accuracy of the information collected. In addition to these, we can use the AHP together with the fuzzy logic to modeling the uncertainties of the specialist's judgments and verify the improvement of the model.

The evaluation of the pairwise comparison matrix's consistency is essential to obtain a model close to reality. In the judgment-making process, individuals are more likely to be inconsistent, so that we can expect an inconsistent pairwise comparison matrix. According to Saaty and Vargas (2012), the inconsistency allows readjusting a system of judgments to receive new data, but it must be admitted without dominating or confusing the consistency. Thus, through the methods created to improve the consistency of positive reciprocal matrices, one can identify the judgment causing the largest perturbation in the matrix consistency. Both methods we used in this paper proved to be efficient, identifying the judgments that caused the largest perturbation in the matrix consistency. We obtained a consistent pairwise comparison matrix with the review of these judgments. However, we must observe the results of these methods with caution, evaluating their real meaning. Saaty and Vargas (2012) state that forced consistency is not desired because a pairwise comparison matrix can be perfectly consistent but irrelevant and far off reality. Given the initial assessment of the expert and the previous researches analyses, we understand that considering the location and type factors of equal importance, as suggested by the second method, made mathematical sense but did not match reality. We performed a new consultation with the expert, resulting in the modified and consistent pairwise comparison matrix.

The modified matrix provided the weights of the risk factors for the obstacle risk classification model. The protrusion factor has the highest weight, having the most considerable influence on risk modeling, and the type factor has not significantly influence risk modeling. However, the type factor improves the model because learning the nature of the obstacle that poses a risk to airspace safety is crucial for adopting risk mitigation actions. In this paper, we considered the relief, buildings, poles, and towers for the type factor. We chose these features mainly because we can rule their heights based on specific laws and because it is difficult to remove them. We can analyze the relief case using the urban city plots and assess their constructive viability. Other features that may also pose risks to the safety at airports are, for example, vegetation, trees, bridges, footbridges, and overpasses. We did not consider vegetation and isolated trees as obstacles because their pruning, removal, or transplantation is not relevant when compared to others features. We did not evaluate bridges, footbridges, and overpasses because the municipality laws impose the elevation limit. However, it is essential to consider such features in future researches. The research sequence consists of applying the proposed model to classifying the risk of obstacles in the protection zone of the Porto Alegre International Airport, quantifying and representing three-dimensionally the risk of these obstacles.

5. Conclusions

In this paper, we discussed the problem of modeling the risk of obstacles in aerodrome protection zones. We defined risk factors with associated risk scores and, through AHP, we determined the weights of the risk factors. The methodology proved to be valid for obtaining a model to classify the risk of obstacles in aerodrome protection zones, proving to be a valuable tool for use in aviation and airports.

The methodology applied gives a multicriteria decision process, assisted and systematic, using consistent risk classification criteria based on an explicit statement of the expert's subjective preferences. The advantage of the proposed methodology is that it can be adaptable for any airport and airspace laws considering the airport's geographic environment condition and their surrounding areas. However, the subjective biases of expert opinions are a limitation of our methodology.

Learning the risk of obstacles to airspace safety is essential to ensure an acceptable operational safety level at airports. Thus, the risk modeling of obstacles in aerodrome protection zones should be used by airport managers to assess risk situations, assisting in the effective management of obstacles and approaches to risk mitigation actions for airspace operations.

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AUTHOR´S CONTRIBUTION

All the authors contributed equally to make the writing of this paper possible, and all authors have read and agreed to the published version of the manuscript.

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APPENDIX

Questionnaire

EXPERT INFORMATION

A. Education level: Higher education

B. Position/Occupation: Engineer

C. Experience in the area of aviation and airports:

( ) up to 10 years ( ) from 11 to 20 years (X) more than 20 years

EXPERT OPINION

To answer the questions, consider the following definitions for the nomenclatures DISTANCE,LOCATION, TYPE, and PROTRUSION, covered in this questionnaire.

- DISTANCE: distance between the obstacle and the nearest airport runway threshold.
- LOCATION: PBZPA's limiting surface in which the obstacle is inserted.
- TYPE: nature of the obstacle (relief, building, pole, antenna, or tower).
- PROTRUSION: how much the obstacle protrudes above each limiting surface of the PBZPA (0.5m, 1m, 2m, etc.).

I. Are the following factors important for assessing the obstacles risk to airports?

DISTANCE (X) yes ( ) no LOCATION (X) yes ( ) no

TYPE (X) yes ( ) no PROTRUSION (X) yes ( ) no

II. Assign a number to the factors according to their relevance:

(1) Not relevant (2) Relevant (3) Very relevant (4) Extremely relevant

(3) DISTANCE (3) LOCATION (3) TYPE (4) PROTRUSION

1. Consider the existence of obstacles near the airport landing/takeoff runway thresholds. Enter five distance ranges. Then, assign a number to these ranges considering the **likely** compromise of safety and regularity of air operations.

(1) Very unlikely (2) Unlikely (3) Likely (4) Very likely (5) Extremely likely

a) (5) 0 to 300 m

b) (4) 300 to 1000 m

c) (3) 1000 to 5000 m

d) (2) 5000 to 10000 m

e) (1) more than 10000 m

2. Consider the limiting surfaces established by airports' PBZPA and the obstacles inserted into these surfaces. Assign a number to the surfaces according to the **likelihood** that an obstacle located on these surfaces will compromise the safety and regularity of air operations.

(1) Very unlikely (2) Unlikely (3) Likely (4) Very likely (5) Extremely likely

(5) Approach Surface (3) Transitional Surface (4) Inner Horizontal Surface

(2) Conical Surface (1) Outer Horizontal Surface

3. Consider the TYPE (nature) of the obstacles. Assign a number to the obstacle type according to its **dangerousness**, considering the compromise of safety and regularity of air operations.

(1) Very little dangerous (2) Little dangerous (3) Dangerous (4) Very dangerous

(5) Extremely dangerous

(4) Relief (4) Building (5) Pole (5) Antenna (5) Tower

4. Consider the PROTRUSION of obstacles above limiting surfaces established by the airports' PBZPA. Assign a number to protrusion ranges considering the **likely** compromise of safety and regularity of air operations.

(1) Very unlikely (2) Unlikely (3) Likely (4) Very likely (5) Extremely likely

(3) 0 to 1.5m (3) 1.6 to 3.0m (4) 3.1 to 4.5m (5) 4.6 to 6.0m (5) more than 6.0m

5. Use the comparison numerical scale below to highlight the relative importance of the factors DISTANCE, LOCATION, TYPE, and PROTRUSION in the study of compromisingsafety and regularity of air operations of the airports.

Comparison numerical scale:

(**1/9**) Factor X is **extremely LESS important** than factor Y.

(**1/7**) Factor X is **very strongly LESS important** than factor Y.

(**1/5**) Factor X is **strongly LESS important** than factor Y.

(**1/3**) Factor X is **moderately LESS important** than factor Y.

(**3**) Factor X is **moderately MORE important** than factor Y.

(**5**) Factor X is **strongly MORE important** than factor Y.

(**7**) Factor X is **very strongly MORE important** than factor Y.

(**9**) Factor X is **extremely MORE important** than factor Y.

a) The DISTANCE factor compared to the LOCATION factor is:

(1/3) (1/5) (1/7) (1/9) (3) (5) (7) (9)

b) The DISTANCE factor compared to the TYPE factor is:

(1/3) (1/5) (1/7) (1/9) (3) (5) (7) (9)

c) The DISTANCE factor compared to the PROTRUSION factor is:

[✓ (1/3)] (1/5) (1/7) (1/9) (3) (5) (7) (9)

d) The LOCATION factor compared to the TYPE factor is:

(1/3) (1/5) (1/7) (1/9) (3) (5) (7) [✓ (9)]

e) The LOCATION factor compared to the PROTRUSION factor is:

[✓ (1/3)] (1/5) (1/7) (1/9) (3) (5) (7) (9)

f) The TYPE factor compared to the PROTRUSION factor is:

[✓ (1/3)] (1/5) (1/7) (1/9) (3) (5) (7) (9)

6. Write your comment or suggestion (optional):