future transportation

Review

Land Use Around Airports: Policies and Methods for Third-Party Risk Assessment—A Review

Paola Di Mascio [1], Raducu Dinu [2], Giuseppe Loprencipe [1] and Laura Moretti [1,*]

[1] Department of Civil, Building and Environmental Engineering, Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy; paola.dimascio@uniroma1.it (P.D.M.); giuseppe.loprencipe@uniroma1.it (G.L.)
[2] AtkinsRéalis, 455, René-Lévesque Ouest, West Montreal, QC H2Z 1Z3, Canada; raducu.dinu@atkinsrealis.com
* Correspondence: laura.moretti@uniroma1.it

Abstract: The development and land use surrounding airports are a concern and interest for airport operators, public communities, business communities, and local authorities. Airport development and operations are governed by both national and international regulations that often extend beyond airport property boundaries. Typical international airports' regulations, recommendations, and guidance documents (e.g., Noise Exposure and Obstacle Limitation Surfaces) and their national counterparts focus on airport land-use planning. Individual third-party risk assessment of airport operations serves as a complementary tool to these regulations, providing means to assess and manage land-use compatibility and control activities near airport perimeters. Developing robust risk assessment models is essential for defining and validating public safety areas and Runway Protection Zones to ensure land-use compatibility and public safety. Although several quantitative risk assessment models exist, significant differences remain in their methodologies and applications. Over the past 20 to 35 years, most models have evolved based on historical data from aircraft accidents. This article provides a comprehensive review of risk analysis methods for areas surrounding airports and presents a quantitative comparison of two specific approaches, the ENAC/Sapienza and ACRP methods, along with their associated calculation software.

Keywords: aviation; airports; accident; safety; risk assessment

check for updates

Citation: Di Mascio, P.; Dinu, R.; Loprencipe, G.; Moretti, L. Land Use Around Airports: Policies and Methods for Third-Party Risk Assessment—A Review. *Future Transp.* **2024**, *4*, 1501–1519. https://doi.org/10.3390/futuretransp4040072

Academic Editor: Lynnette Dray

Received: 27 August 2024
Revised: 9 November 2024
Accepted: 25 November 2024
Published: 2 December 2024

1. Introduction

With the steady increase in air traffic and the consequent need for expanded airport infrastructure, interest in development and land use around airports is growing, particularly concerning the impact on nearby populated areas [1]. Airport development and operations are subject to a range of national and international regulations, recommendations, and guidance documents, many of which influence areas beyond the airport property or perimeter fence. Key regulatory areas, including Noise Exposure [2] and Obstacle Limitation Surfaces and Sectors [3,4], primarily address land-use planning around airports to support safe and minimally disruptive air mobility [5]. At a broader level, the International Civil Aviation Organization (ICAO) [6] mandates aviation safety practices through Annex 19, which requires member states to implement State Safety Programs (SSPs). The SSP framework, alongside the Safety Management System (SMS), outlines essential elements such as Safety Policies & Objectives, Safety Risk Management, Safety Assurance, and Safety Promotion. Within this framework, ICAO's Safety Management Manual [7] identifies Safety Risk Management (SRM) as a key component, comprising hazard identification, safety risk assessment, safety risk mitigation, and risk acceptance. Third-party risk assessment of airport operations aligns with these regulations, providing a method to evaluate land-use compatibility around airports and, when necessary, to limit or control activities near the airport perimeter [8]. Safety risk assessment can be conducted through quantitative [9,10] or qualitative analyses [11,12]. Qualitative approaches often use tools such as bow tie diagrams, risk severity tables, risk matrices, and risk tolerability, according to [7] (Table 1, Table 2, and Table 3, respectively). However, qualitative risk assessments using matrices alone may lack sensitivity to aggravating factors, such as the potential for collisions between aircraft and obstacles in airport-adjacent areas [13]. This limitation underscores the need for enhanced risk assessment methodologies that incorporate more comprehensive quantitative approaches for a clearer evaluation of third-party risks around airports.

Table 1. Example safety risk severity table.

Severity	Meaning	Value
Catastrophic	• Aircraft or equipment destroyed • Multiple deaths	A
Hazardous	• A significant reduction in safety margins, physical distress, or a workload such that operational personnel cannot be relied upon to perform their tasks accurately or completely • Severe injury • Major equipment damage	B
Major	• A significant reduction in safety margins, causing a reduction in the ability of operational personnel to cope with adverse operating conditions as a result of an increase in workload or as a result of conditions impairing their efficiency • Serious incident • Injury to people	C
Minor	• Nuisance • Operating limitations • Use of emergency procedures • Minor incident	D
Negligible	• Few consequences	E

Table 2. Example safety risk matrix.

		Severity				
Probability		Catastrophic A	Hazardous B	Major C	Minor D	Negligible E
Frequent	5	5A	5B	5C	5D	5E
Occasional	4	4A	4B	4C	4D	4E
Remote	3	3A	3B	3C	3D	3E
Improbable	2	2A	2B	2C	2D	2E
Extremely improbable	1	1A	1B	1C	1D	1E

Table 3. Example safety risk tolerability.

Safety Risk Index Range	Safety Risk Description	Recommended Action
5A, 5B, 5C, 4A, 4B, 3A	Intolerable	Take immediate action to mitigate the risk or stop the activity. Perform priority safety risk mitigation to ensure additional or enhanced preventative controls are in place to bring down the safety risk index to tolerable.
5D, 5E, 4C, 4D, 4E, 3B, 3C, 3D,2A, 2B, 2C, 1A	Tolerable	Can be tolerated based on safety risk mitigation. It may require management's decision to accept the risk.
3E, 2D, 2E, 1B, 1C, 1D, 1E	Acceptable	Acceptable as is. No further safety risk mitigation is necessary.

Quantitative methods for assessing third-party risks related to airport operations [14] are well-documented in the literature. These methods focus on evaluating risks to people and infrastructure near airports but are typically independent of oversight by airports or aviation service providers. Over recent decades, various methods have been developed to manage land use and associated risk tolerability at a societal level [15]. These risk assessment approaches around airports differ by country, often through establishing Public Safety Zones (PSZs) and Runway Protection Zones (RPZs). In the U.S., a Guide for Effective Land Use Planning [16] was developed by a Federal Aviation Administration (FAA) Task Force to promote coordinated efforts toward land-use compatibility. Interim policy guidance specific to land use within the RPZ has been available since 2012 [17] and 2013 [18]. More recently, the FAA issued the Advisory Circular (AC) "Airport Land Use Compatibility Planning" [19], which consolidates and updates prior guidance on land-use compatibility, addressing major land-use conflicts impacting public airport operations. However, it does not introduce new standards or requirements, as the FAA lacks authority over land use beyond airport boundaries.

In Canada, updated regulations [20] require formal consultation with stakeholders before development or significant modification of airport infrastructure (i.e., a new runway or runway extension by more than 100 m or 10%). This process mandates collaboration with neighboring land-use authorities, property owners, and, if appropriate, public consultations within a 4000 m radius of the airport boundary.

In Europe, several countries (e.g., the UK [21–25], Ireland [26], and the Netherlands [27,28]) employ a precautionary approach within PSZs, focusing on acceptable levels of individual third-party risk. This method has been widely applied to large European airports [29,30]. Each national model relies on a combination of three submodels [31]: the accident probability model, accident location model, and accident consequence model [32,33]. These models comply with [2] and support a zoning policy to ensure land-use compatibility [34], and they typically incorporate predictive analytics based on historical accident data, forming "fourth-generation models" [35,36]. The retrospective use of accident data allows for the first- to third-generation reactive models. The difference between the first two generations is only in updating the data and accident rates, while the third generation incorporates a curvilinear coordinate system for departures [37]. Fourth-generation models have since evolved to include additional parameters, such as aerodrome design and aircraft performance factors (e.g., runway length, engine power, and environmental conditions), to improve crash location predictions. The following sections will provide further details on the methodologies used in Europe and the United States, offering insights into how these models are applied and adapted for effective airport land-use planning.

2. Review of Methods to Calculate Individual Third-Party Risks Around Airports

This study conducted a systematic literature review following the approach outlined by Kitchenham [38]. It enables a comprehensive identification, analysis, and comparison of policies and methods for third-party risk assessment around airports. The reviewed sources include primary documents, such as scientific papers, standards, and technical regulations, while this manuscript represents a secondary analysis. The review focuses on peer-reviewed articles published between 1996 and 2024 that examine the impact of airport risk assessment on land use in areas surrounding airports. The primary search strategy was automatic with the keywords "land use around airports" + "risk" and "veer-off" using databases such as Scopus, Web of Science, and ICAO resources. Furthermore, a manual search was performed to collect documents published since 2000.

The SLR process included three main phases: planning, conducting, and reporting:

- Planning: This phase defined the need for the SLR and established the following research questions:
    - Which types of quantitative models are employed internationally to assess risk in areas surrounding airports?
    - Which movements contribute to the assessment?

 ◦ What are the main differences between the available models?

- Conducting: This phase involved implementing the search strategy to address the research questions, systematically selecting relevant studies for analysis;
- Reporting results: This phase involved describing the results, addressing the study's objectives, and discussing the findings [39].

After the final application of the work selection strategy, a total of 91 documents were identified: a total of 63 are primary studies (i.e., peer-reviewed indexed research papers), 2 are secondary studies (i.e., reviews), and 26 are classical sources, standards, and regulations. These selected works permitted the authors to critically assess the current state of research and address the proposed research questions.

2.1. European Models

Quantitative risk analysis models for third-party risk assessment have been developed in Europe, specifically in the UK [25,40,41], Ireland [26], and The Netherlands [42–44]. These reactive models fall into the second (i.e., UK and Ireland) and third (i.e., the Netherlands) generations, focusing on accident probability assessment and accident location submodels. British and Dutch models apply certain criteria, such as including only medium and large airports (i.e., those with over 150,000 movements per year), assuming that 90% of flights meet "Western" standards and 70% are precision approaches, and excluding general aviation involving light aircraft. Accident databases extend from 1979 to 1995 for the British and from 1980 to 1997 for the Dutch model, while accident databases span from 1979 to 1995 for the British model and from 1980 to 1997 for the Dutch model. The Irish model follows similar criteria to the British approach but also includes a separate model for light aircraft.

All these models consist of three submodels: accident probability, accident location, and consequence (Figure 1), which collectively estimate individual risk. Only the Dutch model incorporates societal risk [15,28], accounting for the risk across the area based on the actual population distribution around the airport.

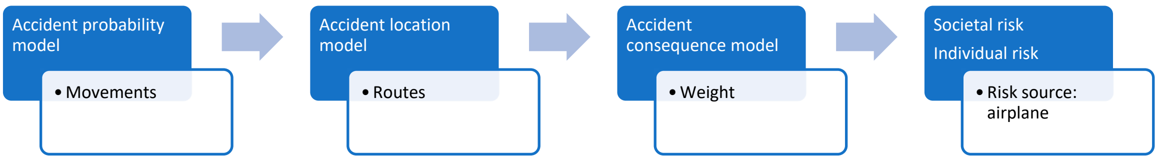

Figure 1. Reactive risk assessment model [28].

All models consider flight maneuvers (i.e., landing undershoot (LDUS), landing overrun (LDOR), take-off overrun (TOOR), and take-off overshoot (TOOS)) and their accidents (Figure 2). Veer-off accidents are overlooked in the standard Dutch, British, and Irish models.

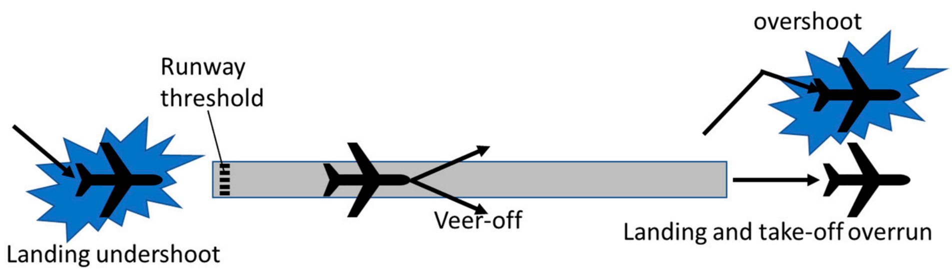

Figure 2. Accident types [28].

The accident probability models estimate the probability of an event based on specific operational conditions, such as the yearly number of movements [28]. None of these models include variance analysis to compare accident probability estimates against the actual statistical locations of accidents. Table 4 presents the accident rates (per million flights) for third-generation aircraft according to the Dutch model [28].

Table 4. Accident rates (per million flights) for third-generation aircraft.

Mode	Period		
	1980–1998	1992–2004	2001–2010
Take-off overrun	0.062	0.046	0.012
Take-off overshoot	0.046	0.015	0.037
Landing overrun	0.062	0.107	0.146
Landing undershoot	0.124	0.107	0.073

The accident probability model retained by the British and Irish models is empirical. It considers aircraft with a 4 Mg Maximum Takeoff Weight Authorized (MTWA). For the Dutch one, the MTWA is 5.7 Mg. Table 5 presents the crash rates for different aircraft classes according to the British and Irish models [41].

Table 5. Accident rates (crash rates) for different classes of aircraft.

Aircraft Class	Crash Rate (Crashes per Million Movements)
Class I jets	1.114
Class II-IV jets	0.148
Eastern jets	0.930
Executive jets	0.270
Turboprops T1	0.270
Turboprops T2	0.733
Turboprops (unclassified)	0.733
Piston-engine	3.000
Other non-commercial	3.000
Miscellaneous	3.000

The accident location model determines the geographic distribution of accidents relative to runways and flight paths, based on historical data for aircraft overruns, veer-offs, and undershoots. A key distinction between the British/Irish and Dutch models lies in the wreckage location approach: the British and Irish models align accident distribution along the runway centerline, while the Dutch model uses the flight path route. In all models, risk assessment centers on the PSZ at each runway end.

The consequence model focused solely on ground impact, excluding passengers and crew, and defines the severity of an accident in terms of the impacted area. The risk at any point surrounding the airport is calculated as the probability of an accident occurring at that point, multiplied by the area affected (or destroyed), representing the risk of fatality for a person at that location due to an aircraft crash. Societal risk can be further evaluated by factoring in population density around the airport [15].

Although acceptable levels of individual risk vary according to regulatory standards, criteria, and specific industry practices [41], a risk threshold of around 1×10^{-6} per year is typically regarded as acceptable [2]. Based on this, zones are defined by threshold risk levels: 1.00×10^{-4} (inner area), 1.00×10^{-5} (intermediate area/Inner PSZ boundary), and 1.00×10^{-6} (outer area/Outer PSZ boundary) yearly [26,40,42]. Land use within these zones is outlined in Tables 6 and 7 for proposed and existing developments, respectively [26].

In the UK, recent updates to the Policy of the Control of the Development in airport PSZ are illustrated in Figure 3 [40]. This policy specifies the dimensions and configuration of PSZs, with an inner boundary, the PSRZ, in red, and an outer boundary, the PSCZ, in blue. The dimensions, particularly the length, of a PSZ are determined based on a risk appraisal that factors in the volume of airport movements. According to the policy, PSZ boundaries must be redefined if a runway is extended or if the landing threshold is adjusted. Local planning authorities are encouraged to apply this risk assessment methodology when PSZ compliance with [40] is not achieved. The standardized PSZ shapes in Figure 1 approximate iso-risk curves derived from risk assessments, aligning with the triangular configuration proposed by [26].

Table 6. New land-use developments.

	Inner PSZ			Outer PSZ [1]		
	Industry [2]	**Housing**	**Vulnerable [3]**	**Industry [2]**	**Housing**	**Vulnerable [3]**
Ireland	NO	NO	NO	YES	YES	NO
The Netherlands	NO	NO	NO	YES	NO	NO
UK	NO	NO	NO	YES	YES	YES

NO—development not permitted, YES—development permitted, [1] for the UK, the Outer PSZ refers to the land beyond the PSZ, [2] Industry—includes offices, [3] Vulnerable—hospitals, schools, and sport stadia.

Table 7. Existing land-use developments.

	Inner PSZ			Outer PSZ [1]		
	Industry [2]	**Housing**	**Vulnerable [3]**	**Industry [2]**	**Housing**	**Vulnerable [3]**
Ireland	Remain	Remain	Remain	Remain	Remain	Remain
The Netherlands	Remain	Remove	Remove	Remain	Remain	Remain
UK	Remain	Remain	Remain	Remain	Remain	Remain

Remove—developments to be removed, Remain—developments to remain and current use can continue, [1] for the UK, the Outer PSZ refers to the land beyond the PSZ, [2] Industry—includes offices, [3] Vulnerable—hospitals, schools, and sport stadia.

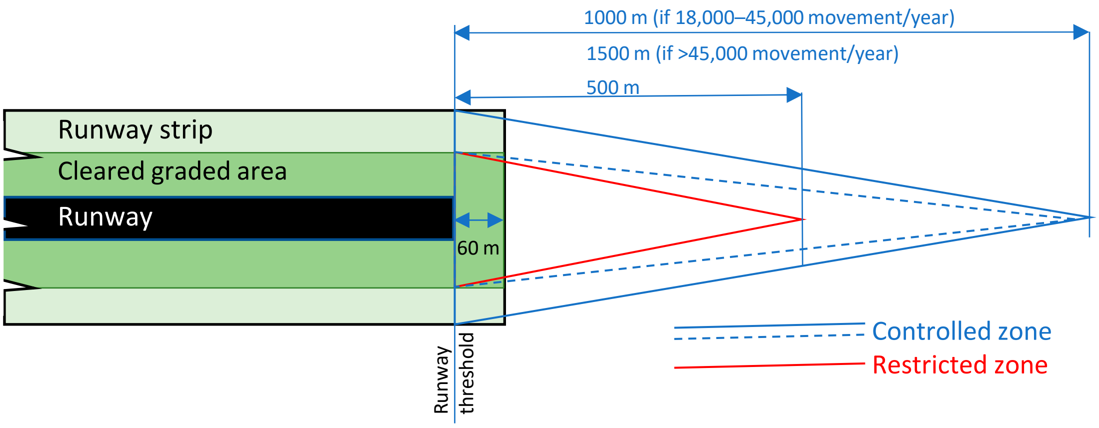

Figure 3. Airport PSZ in the UK [40].

Italian studies on the distribution of air accidents around runways [45] from 1996 to 2022 examined 2508 events during landing, final approach, take-off, and initial climbing [45]. These involved "Western-built and operated" aircraft, with data filtered to exclude companies operating under safety standards and technologies not aligned with Italian norms. The data filtration aligns with international standards [46] but it is not adaptable for other uses [37]. The software tool Spatial Distribution of Aircraft Crashes, SDAC [45], facilitates the analysis and visualization of accident data. Each recorded accident is plotted using a coordinate system, with the y-axis aligned with the runway centerline and the x-axis perpendicular to it, offering a standardized framework for understanding accident locations relative to runway orientation.

The aircraft's position following an accident is determined by the impact location (Figure 4):

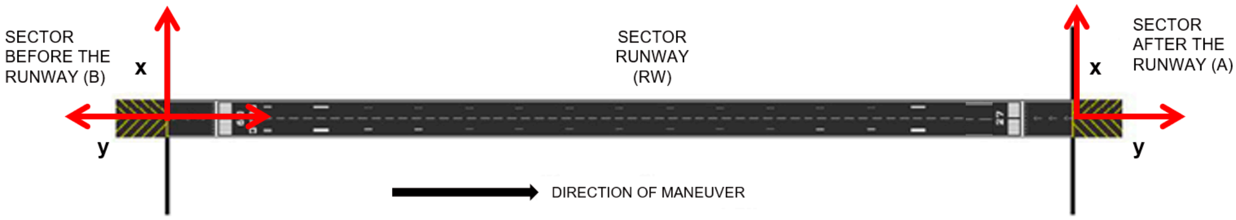

Figure 4. The coordination system(s) in SDAC [45].

- If the accident occurs before the aircraft has touched down on the runway, it is labeled "B" (Before). Here, the *y*-axis points outward, opposite the runway, with the origin of the coordinate system at the first threshold;
- If the accident occurs between the two thresholds, it is marked "RW" (RunWay), with the *y*-axis aligned in the direction of the aircraft's landing trajectory;
- If the aircraft overruns and comes to a stop beyond the threshold, the impact point is designated "A" (After), with the origin of the Cartesian coordinate system set at the second threshold.

The accident probability model aligns with the frameworks in the UK, Ireland, and the Netherlands, comprising two probabilistic distributions: one for take-off (including initial climbing) and another for landing (including approach) accidents. The SDAC tool enables a detailed analysis of the accident distribution with respect to runway length and aircraft categories, including general aviation. The outputs support the development of risk plans for small and medium airports (Figure 5). Conversely, a three-submodel approach is employed to assess risks in areas surrounding the busiest airports (Figure 6).

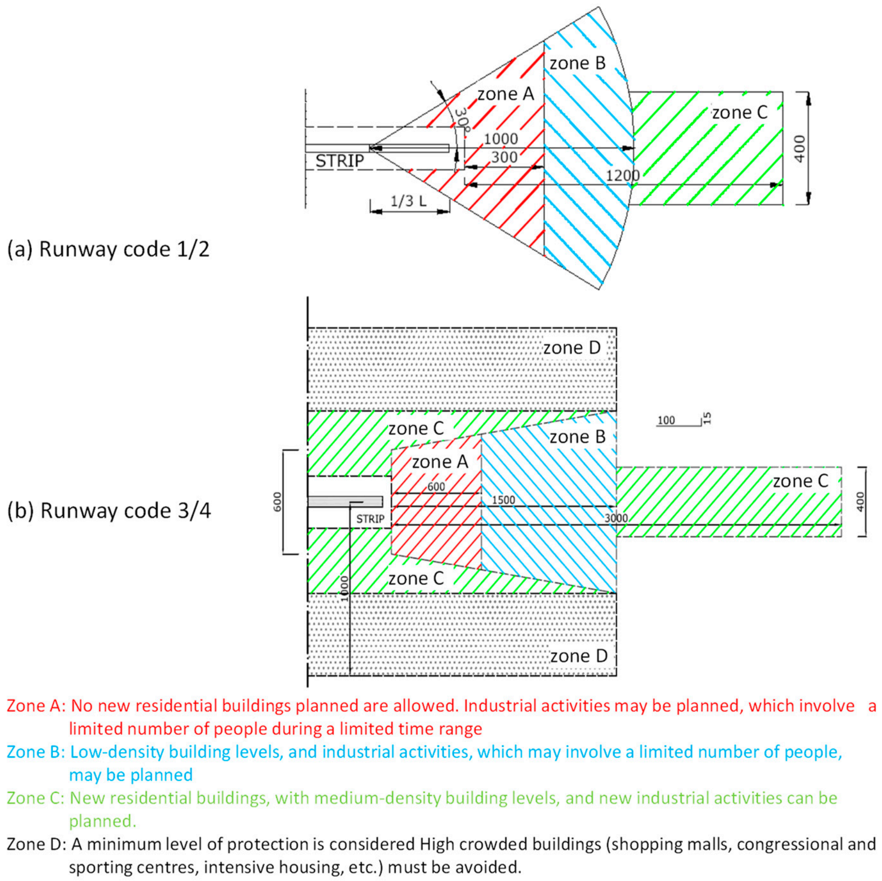

Figure 5. Risk Management Plan in Italy [47,48] (unit: m).

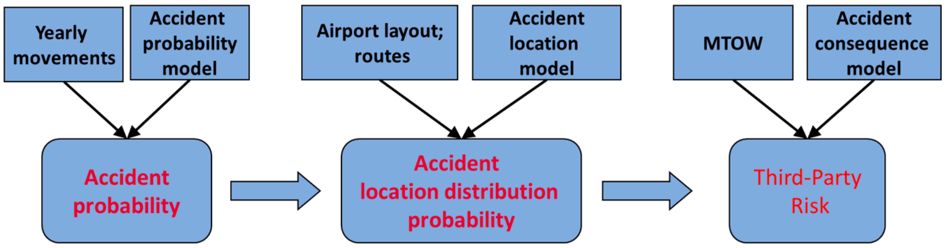

Figure 6. Three-submodel approach [47].

A standardized individual risk assessment model has been developed, drawing from elements of both the Irish model (the probability distribution functions, based on the UK accident database) and the Dutch one (for the calculation of the individual risk and use of a curvilinear coordinate system) [49] to delineate PSZ iso-contours. Consequently, this model is classified as third-generation. The accident probability model applies accident rates specific to each aircraft type, adjusted for the number of movements. For accident location, it uses two probability density distributions: a Weibull distribution coupled with a Gaussian distribution for overruns and landings, and a Gamma distribution for climbs and take-offs. The consequence model assesses impact severity based on third-party individuals on the ground, considering factors such as the affected area, aircraft weight, and wingspan. This model is implemented in the SARA v. 1.0 (Sapienza Airport Risk Analysis) software, which calculates iso-risk contours. SARA enables the definition and validation of PSZs for single-runway, high-traffic Italian airports [48] by varying the traffic mix and volume. Its outputs, validated through previous risk analyses, are valuable for updating risk plans for small and medium-sized airports (fewer than 50,000 movements per year) [50]. Notably, iso-risk contours produced by SARA show significant deviations from existing ICAO-based risk plans, often leading to risk overestimation for small airports or underestimation for small-to-medium airports. All currently available models establish PSZs solely at runway thresholds. In response, the Italian Civil Aviation Authority (ENAC) [47] has proposed a land-use approach that includes a Risk Management Plan and risk assessment for areas around airports. The Risk Management Plan defines zoning and land-use restrictions according to ICAO Runway Codes (see Figure 5), while the risk assessment incorporates a Third-Party Individual Risk Analysis with three defined risk thresholds: 1.00×10^{-4} (internal airport area), 1.00×10^{-5} (intermediate area), and 1.00×10^{-6} (external area, extending beyond the designated outer limit if exceeded).

2.2. ACRP Model

In the U.S., research conducted under the Airport Cooperative Research Program (ACRP) and Federal Aviation Administration (FAA) [51,52] has led to the development of models for accident frequency and location, specifically for Runway Safety Areas (RSAs) and Runway Protection Zones (RPZs) [53]. The resulting risk assessment model relies on three submodels. The ACRP accident probability model employs a logistic equation that incorporates variables related to causal and contributing factors of an event, drawing on Normal Operations Data (NOD) based on U.S. data [54]. Unlike previous models that rely solely on historical accident rates [55,56], the NOD approach allows for a predictive, proactive model—categorized as fourth-generation—tailored to each flight maneuver. However, the availability of NOD may be limited outside North America [57]. The ACRP location model uses five complementary cumulative probability distribution curves, accounting for take-off overruns/veer-offs and landing undershoots/overruns/veer-offs. These distributions, when multiplied by accident frequency, yield a probability frequency distribution. Both longitudinal and lateral accident distributions use exponential functions derived from historical accident location data. The ACRP consequence model assesses risk based on occurrence likelihood, severity level, and population density within the RPZ, accounting for variations in aircraft type and airport facilities. This model estimates both societal and individual risk using the publicly available "RPZ Risk Assessment Tool (RPZ_RAT)" [58], which supports airport sponsors and planners in conducting RPZ risk assessments. The dimensions of RPZs are determined by FAA standards [59] and vary based on aircraft movement, runway reference code, and approach type. As shown in Figure 7, the largest RPZ measures 2500 feet by 1000 feet by 1750 feet (762 m × 305 m × 534 m) for approaches with visibility less than ¾ mile.

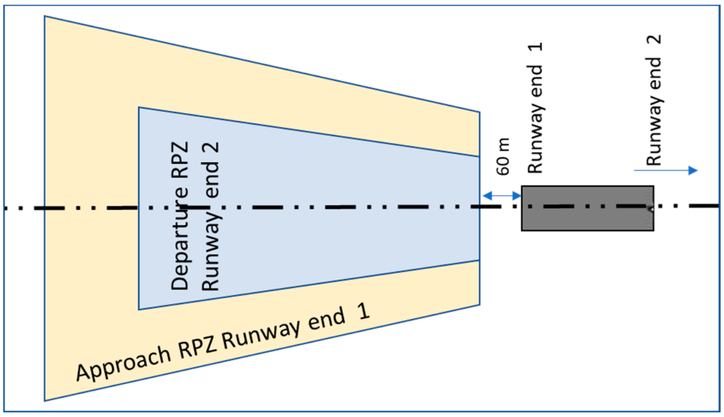

Figure 7. RPZ according to [59].

2.3. Comparison of ENAC/Sapienza (SARA) and ACRP Models

Following the review of risk assessment approaches, the Italian and ACRP models were analyzed and compared based on the accident probability model, accident databases used to develop the location probability model, accident location probability model, and calculation of the risk values through case studies.

2.3.1. Accident Probability Models

The accident probability model used in SARA relies on historical accident aircraft rates. It calculates the weighted average accident rate (R) per movement according to Equation (1):

$$R = \frac{R_1 N_1 + \cdots + R_n N_{n1}}{N} = \frac{\sum_{i=1}^{n} R_i N_i}{N} \quad (1)$$

where R_i is the aircraft (i) accident rate, N_i is the number of the ith aircraft movements, and n is the number of aircraft in the traffic mix.

Then, R is distributed according to the weight of each type of accident according to the phase of flight assumed from the Irish model [26] and listed in Table 8.

Table 8. Weight of each type of accident on the accident rate.

Accident Type	Weight on Accident Rate R
LDUS—Landing undershoot	0.52
LDOR—Landing overrun	0.20
TOOS—Take-off overshoot	0.20
TOOR—Take-off overrun	0.08

The ACRP probability model based on NOD considers weather conditions, aircraft performance, and runway characteristics and conditions. These independent variables are causal and contributing factors for accidents [51]. TORA/LDA values and the aircraft runway distance required for operating conditions are key runway criticality factors. The model's fundamental structure is based on the logistic Equation (2):

$$f_{excursion} = \frac{1}{1 + e^{-(b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + \cdots + b_n X_n)}} \quad (2)$$

where $f_{excursion}$ is the probability of an accident type under certain operational conditions (and variables), X_i represents independent variables (e.g., weather, aircraft type, criticality factor), and b_i represents regression coefficients, $i = 1, \ldots, n$.

The models were developed by using forward stepwise logistic regression and backward stepwise regression [53]. They provide the parameters of the 32 variables included in five frequency models, one for each accident type in Table 8 and landing veer-offs (LDVOs).

2.3.2. Accident Databases

SARA's accident probability model relies on data from the Irish model, which, in turn, is based on the British accident database. The British database includes 354 events from first-world airports between 1970 and 1995 [41]. These data provide a longitudinal distribution of selected accidents up to 4500 m from the runway threshold and a lateral distribution within 500 m from the runway centerline.

In contrast, ACRP uses a database of 1414 events occurring between 1980 and 2014, collected exclusively from 78 U.S. airports [54]. This dataset covers incidents within 2 miles (3.21 km) of the runway threshold and up to 4500 ft (1.2 km) laterally from the runway centerline, consistent with the RPZ definition (maximum length of 765 m) and focusing risk assessment within the RPZ. By limiting the spatial scope of accident data, the model produces smaller risk contours compared to those based on broader datasets.

2.3.3. Accident Location Models

The accident location model in SARA also adopts the Irish model's approach and uses two PDFs [57] to estimate accident probability density within the coordinate system in Figure 8 where 1 and 2 refer to the runway thresholds.

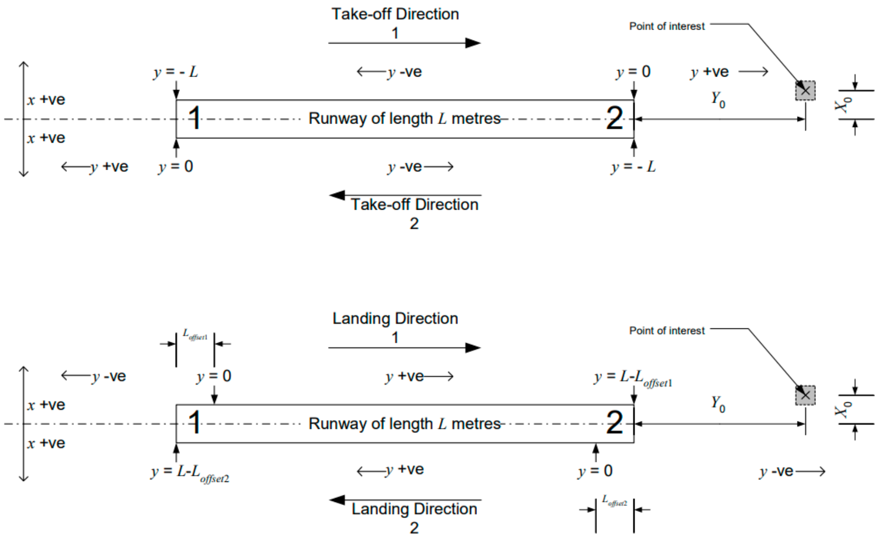

Figure 8. The coordination system(s) in SARA.

The first distribution has y as the independent variable (ordinate) as a Gamma PDF (longitudinal distribution) (Equation (3)):

$$g(y) = p\frac{1}{\beta^{\alpha}\Gamma(\alpha)}y^{\alpha-1}\exp\left[-\left(\frac{y}{\beta}\right)^{\alpha}\right] \quad (3)$$

where $\Gamma(\alpha)$ is Euler's gamma function, β and α are regression coefficients (they assume different values for each type of accident considered: LDUS, LDOR, TOOR, TOOS), and p is the fraction of movements that have $y > 0$ according to Figure 8.

The second distribution has x as the independent variable (abscissa) as a Weibull PDF (transversal distribution) (Equation (4)):

$$h(x,y) = \frac{1}{2}\frac{\alpha}{\beta^{\alpha}}|y|^{\alpha c}|x|^{\alpha-1}\exp\left[-\left(\frac{|x|}{\beta}\right)^{\alpha}|y|^{\alpha c}\right] \tag{4}$$

where α, β, and c are regression coefficients for each type of accident considered (LDUS, LDOR, TOOR, TOOS), and x and y are the coordinates of a given location (the point of interest in Figure 8).

The ACRP approach is based on historical accident data. Four sets of complementary cumulative probability models have been developed for the longitudinal distribution (Equation (5)), and the veer-off has been omitted from the model:

$$g(x \geq x_1) = e^{a\ x_1^b} \tag{5}$$

where $g(x \geq x_1)$ is the probability that the overrun/undershoot distance along the runway centerline beyond the runway end is greater than x; x_1 is a given location or distance beyond the runway end; and a and b are regression coefficients.

The non-linear exponential functions achieved an excellent fit to the data, with R^2 values exceeding 0.99 for all accident types [52]. For the lateral distribution, regression models were applied to fit the data (Equation (6)):

$$h(y \geq y_1 | x \geq x_1) = \frac{1}{1 + e^{(a_1 \cdot x_1^{b_1} + a_2 \cdot y_1^{b_2} + c)}} \tag{6}$$

where x_1 and y_1 are the coordinates of a given location, and a_1, b_1, a_2, b_2, and c are regression coefficients.

R^2 values of all the accident location models exceed 0.97, except LDUS, which has an R^2 equal to 0.88.

In both models, the accident probability density is determined by multiplying the longitudinal and lateral distributions (i.e., g and h, respectively), as in Equation (7):

$$L(x \geq x_1, y \geq y_1) = g(x \geq x_1) \times h(y \geq y_1 | x \geq x_1) \tag{7}$$

where L is the accident likelihood, x_1 is the distance from the runway threshold, and y_1 is the distance from the extended runway centerline.

Compared to SARA, ARCP demonstrates a stronger fit to the data, with notably high R^2 values. This is largely due to the higher concentration of accident data near the runway in the ACRP database. However, the fit of each model is influenced by the differences in accident data dispersion across databases. Furthermore, boundary conditions, such as aircraft performance and operational weather conditions, are specifically considered in the ACRP model, while the SARA model estimates accident probability based on historical accident data alone.

2.3.4. PSZ/RPZ Dimensions

The PSZ/RPZ dimensions impact risk calculations in each model. SARA calculates iso-risk contours (i.e., 1.00×10^{-4}, 1.00×10^{-5}, and 1.00×10^{-6}) according to the Italian regulation, whatever the PSZ dimensions. In contrast, ACRP applies FAA-defined RPZ dimensions and assesses the risks solely within the specified RPZ boundary. Conversely, SARA determines the assessment area automatically based on the statistical distribution of accident data, while ACRP allows users the flexibility to expand the RPZ for a more comprehensive risk analysis. Both models require updates to the accident databases to ensure accuracy when applied to different geographical regions.

2.3.5. Case Study

Finally, the outputs from the SARA and ACRP tools were compared for two airports herein not disclosed for privacy reasons. In the case studies, the American RPZ was selected to match the area of the Italian PSZ, allowing for comparable risk assessment areas.

The first analysis involved a third-party risk assessment for an airport with a 3330 m runway, handling around 70,000 yearly movements across 58 aircraft types. The iso-risk/crush likelihood contours generated by SARA and ACRP are shown in Figure 9a,b, respectively. Although the calculated risk magnitudes are comparable, the contour shapes differ significantly. SARA calculates risk from the runway end, while ACRP bases its calculations from the start of the Runway Safety Area (RSA), aligning with ICAO Annex 14's Runway End Safety Area (RESA) definition [3]. Moreover, ACRP considers the runway required distance versus aircraft performance via NOD, and the runway's declared distances such as ASDA and LDA. In contrast, SARA uses the total runway length for the take-off movements and the LDA for landings.

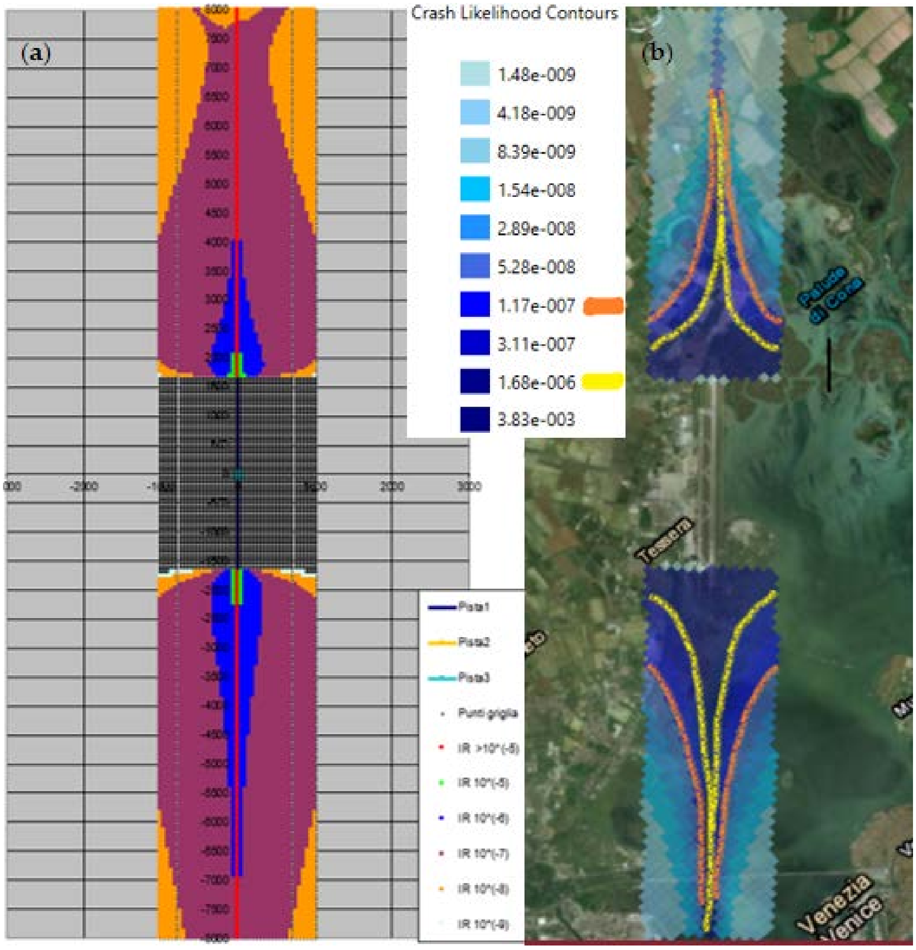

Figure 9. Case study 1: Airport no. 1—single runway: SARA output (**a**) and ACRP output (**b**).

The second case study examined third-party risk for two parallel 3900 m runways, accommodating 260,000 yearly movements across 86 aircraft types [60]. The results in Figure 10 confirm similar trends: contour shapes differ as in the first case study, and dimensions are similar at Runway End 1 but diverge at Runway End 2. This variation results from the different analytical approaches: SARA's contours are based on movement numbers, while ACRP also incorporates climatic conditions. Favorable wind conditions at Airport 2 contribute to smaller contours in ACRP's analysis.

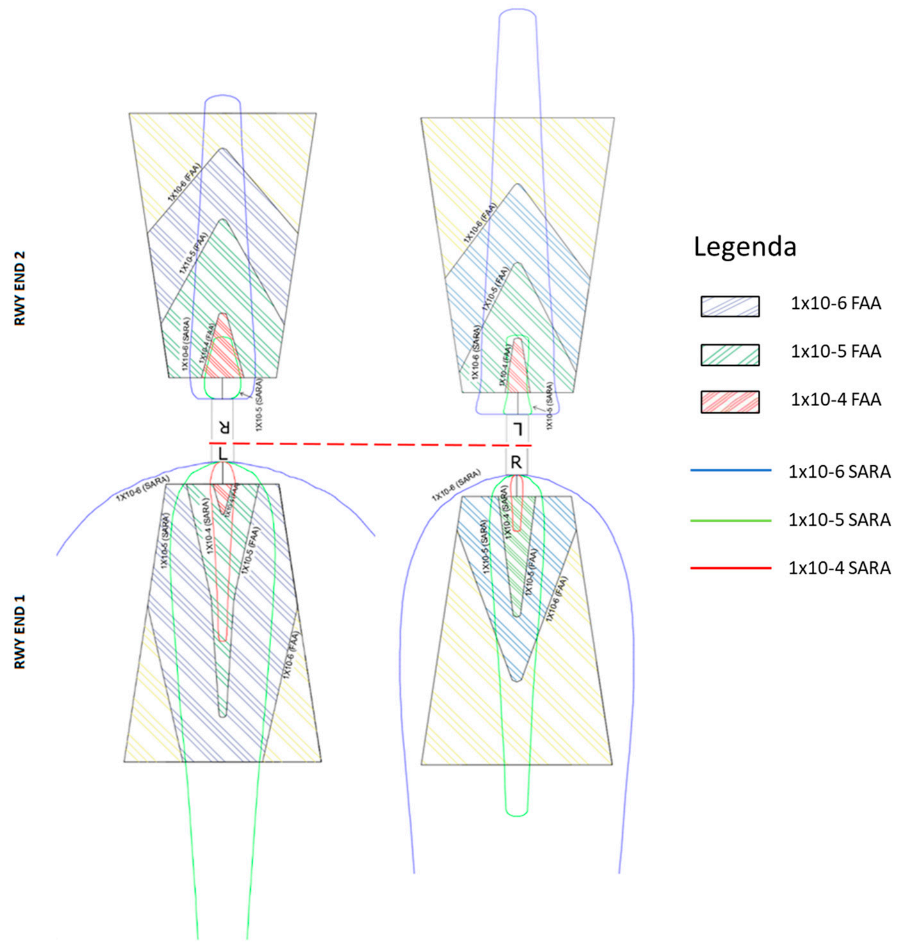

Figure 10. Case study 2: Airport no. 2—two runways.

Table 9 details the maximum dimensions (width and length) of each contour calculated by SARA for both case studies, providing a basis for comparison with ACRP's predefined assessment area. Indeed, ACRP evaluates risk only within a user-defined area, which, in these case studies, was set to the maximum dimensions of the 1.00×10^{-6} iso-risk previously calculated by SARA.

Table 9. Maximum dimensions of the risk contours defied by SARA.

Airport	Yearly Movements	Runway Threshold	Risk	SARA Contours Width (m)	Length(m)
Case 1	69,287	04	1.00×10^{-6}	691	5348
			1.00×10^{-5}	165	829
		22	1.00×10^{-6}	697	2798
			1.00×10^{-5}	210	827
Case 2	259,133	16R	1.00×10^{-6}	648	5032
			1.00×10^{-5}	152	969
		34L	1.00×10^{-6}	229	1124
			1.00×10^{-5}	77	221
		16L	1.00×10^{-6}	1140	9125
			1.00×10^{-5}	283	2315
		34R	1.00×10^{-6}	874	874
			1.00×10^{-5}	100	179

3. Veer-Off Risk Assessment

In the U.S., significant research was conducted under ACRP Project 4-14, leading to the development of the "Lateral Runway Safety Area Risk Analysis" (LRSARA v. 1.1) software tool. It uses a Runway veer-off location Distribution Risk Assessment Model and a Reporting Template [61] to assess veer-off risk. The accident database supporting this model runs from 1982 to 2011, with approximately 90% of the data sourced from U.S. records and the remaining 10% from ten other countries with similar aviation safety profiles [62]. The project report addresses challenges in data availability, particularly for incidents with minor consequences, and suggests methods for gathering such data to enhance model accuracy [63]. The probability estimation in LRSARA aligns with the RPZ risk assessment approach, utilizing NOD. The calculated veer-off risk at the runway strip boundary (in the order of 1.00×10^{-7} [64]) and at the airport fence (approximately 1.00×10^{-10} [65]) fall below the acceptable threshold of 1.00×10^{-6} for third-party exposure.

In the last decade, quantitative studies have expanded to assess veer-off risks for both passenger and cargo flights, covering accidents from 1953 to 2016 [66]. Global statistical data support the estimation of veer-off frequency, wreckage location, and potential damage, allowing for precise risk calculations when an aircraft departs the runway [67–69]. Bayesian networks [70–73] and likelihood-based approaches have been employed to estimate runway veer-off risk [74]. A cumulative probability distribution model proposed by [66] consists of an exponential curve described by the Poisson distribution (Equation (8)) [75]:

$$p_x = P(X_\lambda = x) = \frac{(\lambda t)^x}{x!} e^{-\lambda t} \quad (8)$$

where λ represents the mean, variance, and prevision values of the distribution (i.e., the number of events per average interval between two consecutive events).

The results indicate that the average frequency of a veer-off accident varies between 2.13×10^{-7} and 5.22×10^{-9} depending on the boundary conditions [76] (Figure 11).

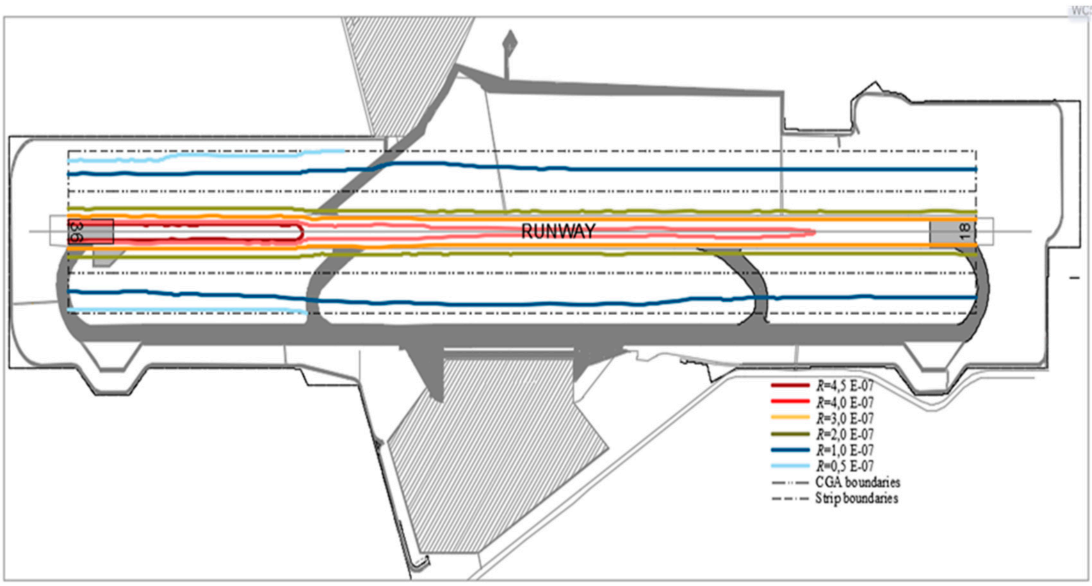

Figure 11. Iso-risk curves.

This analysis enables the calculation of veer-off probabilities at any airport by accounting for specific local conditions, such as the number and type of aircraft, movement types, subgrade bearing capacity, and weather conditions [77,78]. Existing quali-quantitative damage models assess mechanical consequences based on wreckage location [66] and consider site-specific obstacles surrounding the runway to estimate a severity index [79,80].

The causes and consequences of recent veer-off accidents [81] help define cumulative frequency and severity classes, providing a basis for assessing the current level of veer-off risk for each ICAO runway code. Veer-off risk is calculated as the product of probability and damage values, derived through a combination of analytical equations. Iso-risk curves around the runway [64] visually represent the current safety conditions, helping identify areas of higher risk.

By comparing the actual risk level with target risk levels near the runway, airport managers have a practical, unbiased tool for strategic decision-making [82,83]. Di Mascio et al. [83] analyzed current risk levels and recommended enlarging the cleared and graded area beyond the ICAO requirements, proposing dimensional and geotechnical measures to mitigate veer-off risk [84].

4. Conclusions

Recent advances in quantitative approaches have the potential to significantly enhance risk assessment in operational airport safety. This primary review paper aimed to examine and analyze existing third-party risk assessment models suitable for implementation across airports of varying sizes and traffic volumes.

The reviewed models share a common structure, comprising three submodels: an accident probability model, an accident location model, and a consequence model. Variations among these models primarily stem from differences in the accident databases, covered periods, and methods for accident distribution. Typically, historical accident data served as the basis for model development, with the most notable variations among models arising in the treatment of crash location data. Crash location models can be classified into four generations based on the analytical techniques applied to the data. The first and second generations use historical data reactively, whereas the third generation is still reactive but introduces a curvilinear coordinate system for location modeling. The fourth generation further incorporates factors such as airport design (e.g., runway length and available runway distance) and aircraft performance (e.g., engine available power and weather conditions), enabling a more accurate prediction of crash locations.

A comparison of several European and North American models and polices, with differing PSZ/RPZ requirements, reveals distinct methodological approaches. Specifically, the SARA model (third-generation) used in Italy and the ARCP model (fourth-generation) developed in the U.S. were analyzed through two case studies. These studies highlight the differences in model applicability within “Western” operational standards, which typically assume Western air carriers [85], maintenance standards, and crew training. Such models may be less representative of “non-standardized” operational conditions where the accident database or coefficients differ from those used in these models [86–90].

While the order of magnitude for calculated risks remains comparable across models, the shape of risk contours varies. This difference can be attributed to each model’s unique database and probability models, including factors such as the number of accidents, covered period, and accident distribution. For example, ARCP relies on NOD as a key component, while SARA bases its accident location model on Irish/British distribution curves. Additionally, ACRP’s methodology includes the runway required distance against aircraft performance and runway declared distances (ASDA and LDA), unlike SARA’s approach. Lastly, SARA identifies the risk contours according to Italian regulations (10^{-4}, 10^{-5}, and 10^{-6} iso-risk levels), while ACRP calculates risk within FAA-standardized RPZs. In conclusion, while both models offer valuable insights, the choice of model should consider the operational context, regulatory requirements, and specific design and performance factors to ensure accurate risk assessment tailored to diverse airport environments.

Author Contributions: Conceptualization, P.D.M. and G.L.; methodology, P.D.M. and G.L.; software, R.D.; validation, L.M., G.L. and R.D.; formal analysis, R.D.; investigation, P.D.M.; writing—original draft preparation, P.D.M., R.D. and L.M.; writing—review and editing, P.D.M. and L.M.; supervision, P.D.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are unavailable due to confidentiality requirements of the case study authorities.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Smith, E.J. Quantifying the risk of aircraft crashes near an airport. *Am. Astronaut. Soc. Sci. Technol. Ser.* **1996**, *88*, 35–47.
2. ICAO. *Airport Planning Manual, Part II—Land Use and Environmental Management*, 4th ed.; International Civil Aviation Organization (ICAO): Montreal, QC, Canada, 2018; Volume Doc 9184.
3. ICAO. *Annex 14—Aerodromes, Volume I—Aerodrome Design and Operations*, 8th ed.; International Civil Aviation Organisation: Montreal, QC, Canada, 2018; Volume I.
4. ICAO. *Airport Services Manual, Part 6—Control of Obstacles*, 2nd ed.; International Civil Aviation Organisation: Montreal, QC, Canada, 1983.
5. Caves, R.E. Control of risk around airports. *Built Environ.* **1996**, *22*, 223–233.
6. ICAO. *Annex 19—Safety Management*, 2nd ed.; International Civil Aviation Organization: Montreal, QC, Canada, 2016.
7. ICAO. *Doc 9859—Safety Management Manual*, 4th ed.; International Civil Aviation Organization: Montreal, QC, Canada, 2018.
8. da Silva, B.A.C.; Santos, G.S.; Gomes, R.d.A. Land use policy in the vicinity of airports: Analysis and lessons learned from the Brazilian situation. *Land Use Policy* **2020**, *90*, 104314. [CrossRef]
9. Iervolino, I.; Accardo, D.; Tirri, A.E.; Pio, G.; Salzano, E. Quantitative risk analysis for the Amerigo Vespucci (Florence, Italy) airport including domino effects. *Saf. Sci.* **2019**, *113*, 472–489. [CrossRef]
10. Guerra, L.; Murino, T.; Romano, E. Airport system analysis: A probabilistic risk assessment model. *Int. J. Syst. Appl. Eng. Dev.* **2008**, *2*, 52–65.
11. Cokorilo, O. Quantified risk assessment modelling of aircraft landing operations. *Sci. Res. Essays* **2011**, *6*, 4406–4413. [CrossRef]
12. Wilke, S.; Majumdar, A.; Ochieng, W.Y. Airport surface operations: A holistic framework for operations modeling and risk management. *Saf. Sci.* **2014**, *63*, 18–33. [CrossRef]
13. Moretti, L.; Dinu, R.; Di Mascio, P. Collision risk assessment between aircraft and obstacles in the areas surrounding airports. *Heliyon* **2023**, *9*, e18378. [CrossRef]
14. Aalmones, R.; Erkamp, R.; Cheung, Y.S.; Van Nieuwpoort, R. Performance improvements for calculations of third party risk around airports. *WIT Trans. Built Environ.* **2013**, *134*, 447–458.
15. Piers, M. Methods and Models for the Assessment of Third Party Risk Due to Aircraft Accidents in the Vicinity of Airports and Their Implications for Societal Risk. In *Quantified Societal Risk and Policy Making. Technology, Risk, and Society*; Jorissen, R.E., Stallen, P.J.M., Eds.; Springer: Boston, MA, USA, 1998; Volume 12. [CrossRef]
16. Federal Aviation Administration. Land Use Compatibility and Airports, a Guide for Effective Land Use Planning. Available online: https://www.faa.gov/sites/faa.gov/files/about/office_org/headquarters_offices/apl/III.B.pdf (accessed on 23 August 2024).
17. Federal Aviation Administration. *Interim Guidance on Land Use within a Runway Protection Zone*; FAA: Washington, DC, USA, 2012.
18. Stevens, N.; Baker, D. Land Use Conflict Across the Airport Fence: Competing Urban Policy, Planning and Priority in Australia. *Urban Policy Res.* **2013**, *31*, 301–324. [CrossRef]
19. Federal Aviation Administration. *Airport Land Use Compatibility Planning*; Advisory Circular 150/5190-4B; FAA: Washington, DC, USA, 2022.
20. Minister of Justice. *Canadian Aviation Regulations*; Minister of Justice: Ottawa, ON, Canada, 2022.
21. Cowell, P.G.; Gerrard, R.; Paterson, D.S. *A Crash Location Model for Use in the Vicinity of Airports*; National Air Traffic Services Ltd.: London, UK, 1997.
22. Cowell, P.G.; Foot, P.B.; Gerrard, R.J.; Kent, D.; Manson, S.M.; Rivoire, A. *A Methodology for Calculation Individual Risk Due to Aircraft Accidents Near Airports*; National Air Traffic Services Ltd.: London, UK, 2000.
23. Environmental Resources Management (ERM). *Maximum Aircraft Movement Data and the Calculation of Risk and PSZs: Cork Airport*; DT & DoEHLG 7608; ERM: Dublin, Ireland, 2005.
24. Environmental Resources Management (ERM). *Maximum Aircraft Movement Data and the Calculation of Risk and PSZs: Shannon Airport*; DT & DoEHLG 7608; ERM: Dublin, Ireland, 2005.
25. UK Department for Transport. *Control of Development in Airport Public Safety Zones*; Department for Transport: London, UK, 2010.
26. Environmental Resources Management (ERM). *Maximum Aircraft Movement Data and the Calculation of Risk and PSZs: Dublin Airport*; DT & DoEHLG 7608; ERM: Dublin, Ireland, 2005.
27. Roelen, A.L.; Bellamy, L.J.; Hale, A.R.; Molemaker, R.J.; Paassen, M.V. *Feasibility of the Development of a Causal Model for the Assessment of Third Party Risk Around Airports, Part 1: Main Report*; NLR-CR-2000–189-PT-1; NLR: Amsterdam, The Netherlands, 2000.
28. Cheung, Y.S.; de Haij, L.; de Jong, R. *Development of NLR Third Party Risk Model and Its Application in Policy and Decision-Making for the Airports in the Netherlands*; National Aerospace Laboratory NLR: Amsterdam, The Netherlands, 2013.

29. Assessment of Third Party Risk Around Zürich Airport. NLR-CR-2014-215—July 2014. Available online: https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.bazl.admin.ch/dam/bazl/de/dokumente/Sicherheit/Infrastruktur/Sachplan_Infrastruktur_der_Luftfahrt/SIL%25202%2520ZRH%2520Mitwirkung/sil-zrh-dok-a4-anhang-third-party-risk.pdf.download.pdf/SIL%2520ZRH%2520Dok,%2520A4%2520Anhang,%2520third%2520party%2520risk.pdf&ved=2ahUKEwib1O3Ex8eJAxXUpP0HHZJ5N7g4FBAWegQIFBAB&usg=AOvVaw3F-vYi_3c4wgnNnYqzzoWx (accessed on 16 November 2024).
30. Hale, A. Risk contours and risk management criteria for safety at major airports, with particular reference to the case of Schiphol. *Saf. Sci.* **2002**, *40*, 299–323. [CrossRef]
31. Hale, A. Regulating airport safety: The case of Schiphol. *Saf. Sci.* **2001**, *37*, 127–149. [CrossRef]
32. Aho, E. *Third Party Risk Around Vantaa Airport of Helsinki*; IVO International Ltd. for Finnish Civil Aviation Authority: Helsinki, Finland, 1995.
33. Eddowes, M.J. *Risk of Ground Fatalities from Aircraft Crash Accidents at Manchester Airport*; Proof of evidence in Manchester Airport Second Runway Public Inquiry; Manchester Joint Action Group: Manchester, UK, 1994.
34. Bełej, M.; Cellmer, R.; Foryś, I.; Głuszak, M. Airports in the urban landscape: Externalities, stigmatization and housing market. *Land Use Policy* **2023**, *126*, 106540. [CrossRef]
35. Galagedera, S.D.; Pasindu, H.R.; Adikariwattage, V. Analysis of Aircraft Veer off Probability at Runway High Speed Exits. In Proceedings of the 5th International Multidisciplinary Moratuwa Engineering Research Conference, Moratuwa, Sri Lanka, 3–5 July 2019; pp. 527–532.
36. Netjasov, F.; Janic, M. A review of research on risk and safety modelling in civil aviation. *J. Air Transp. Manag.* **2008**, *14*, 213–220. [CrossRef]
37. Tan, E.; Warren, N.; Gleave, D.; Pitfield, D. *A Review and Statistical Modelling of Accidental Aircraft Crashes Within Great Britain*; No. MSU/2014/07; Health and Safety Laboratory and Loughborough University: Loughborough, UK, 2014; Volume 44, pp. 1–158.
38. Kitchenham, B. Procedures for performing systematic reviews. *Keele UK Keele Univ.* **2004**, *33*, 1–26.
39. Van Wee, B.; Banister, D. How to Write a Literature Review Paper? *Transp. Rev.* **2016**, *36*, 278–288.
40. Environmental Resources Management (ERM). *Calculation of Third Party Individual Risk: Determining Public Safety Zones for Airports*; DT & DoEHLG 7608; ERM: Dublin, Ireland, 2005.
41. Evans, A.W.; Foot, P.B.; Mason, S.M.; Parker, I.G.; Slater, K. *Third Party Risk Near Airports and Public Safety Zone Policy*; National Air Traffic Services Limited: London, UK, 1997.
42. Ale, B. Risk assessment practices in The Netherlands. *Saf. Sci.* **2002**, *40*, 105–126. [CrossRef]
43. Ale, B.; Piers, M. The assessment and management of third party risk around a major airport. *J. Hazard. Mater.* **2000**, *71*, 1–16. [CrossRef]
44. Ale, B.J.M.; Bellamy, L.J.; Roelen, A.L.C.; Cooke, R.M.; Goossens, L.H.J.; Hale, A.R.; Kurowicka, D.; Smith, E. Development of a Causal Model for Air Transport Safety. In Proceedings of the ASME 2005 International Mechanical Engineering Congress and Exposition. Engineering/Technology Management, Orlando, FL, USA, 5–11 November 2005; ASME: New York, NY, USA, 2005; pp. 107–116. [CrossRef]
45. Cardi, A.; Di Mascio, P.; Di Vito, M.; Pandolfi, C. Distribution of air accidents around runways. *Procedia—Soc. Behav. Sci.* **2012**, *53*, 861–870. [CrossRef]
46. Eddowes, M.; Hancox, H.; MacInnes, A. *Final Report on the Risk Analysis in Support of Aerodrome Design Rules*; Norwegian Civil Aviation Authority: Olso, Norway, 2001.
47. Ente Nazionale per l'Aviazione Civile (ENAC). *Policy di Attuazione dell'art. 715 del Codice della Navigazione: Definizione della Metodologia e della Policy di Attuazione del Risk Assessment*; Ente Nazionale per l'Aviazione Civile: Rome, Italy, 2010.
48. Di Mascio, P.; Perta, G.; Cantisani, G.; Loprencipe, G. The Public Safety Zones around Small and Medium Airports. *Aerospace* **2018**, *5*, 46. [CrossRef]
49. Attaccalite, L.; Di Mascio, P.; Loprencipe, L.; Pandolfi, C. Risk Assessment Around Airport. *Procedia Soc. Behav. Sci.* **2012**, *53*, 852–861. [CrossRef]
50. Di Mascio, P.; Loprencipe, G. Risk analysis in the surrounding areas of one-runway airports: A methodology to preliminary calculus of PSZs dimensions. *ARPN J. Eng. Appl. Sci.* **2016**, *11*, 13641–13649.
51. Wong, D.K.Y.; Pitfield, D.E.; Caves, R.E.; Appleyard, A.J. The development of a more risk-sensitive and flexible airport safety area strategy: Part I. The development of an improved accident frequency model. *Saf. Sci.* **2009**, *47*, 903–912. [CrossRef]
52. Wong, D.K.Y.; Pitfield, D.E.; Caves, R.E.; Appleyard, A.J. The development of a more risk-sensitive and flexible airport safety area strategy: Part II. Accident location analysis and airport risk assessment case studies. *Saf. Sci.* **2009**, *47*, 913–924. [CrossRef]
53. National Academies of Sciences Engineering and Medicine (Ed.) *Analysis of Aircraft Overruns and Undershoots for Runway Safety Areas (ACRP Report 3)*; The National Academies Press: Washington, DC, USA, 2008.
54. Airport Cooperative Research Program. *Improved Models for Risk Assessment of Runway Safety Areas*; ACRP Report 50; The National Academies Press: Washington, DC, USA, 2011.
55. Trucco, P.; De Ambroggi, M.; Leva, M.C. Topological risk mapping of runway overruns: A probabilistic approach. *Reliab. Eng. Syst. Saf.* **2015**, *142*, 433–443. [CrossRef]
56. Li, X.; Zhang, L.; Shang, J.; Li, X.; Qian, Y.; Zheng, L. A Runway Overrun Risk Assessment Model for Civil Aircraft Based on Quick Access Recorder Data. *Appl. Sci.* **2023**, *13*, 9828. [CrossRef]

57. Yousefi, Y.; Karballaeezadeh, N.; Moazami, D.; Sanaei Zahed, A.; Mohammadzadeh, S.D.; Mosavi, A. Improving Aviation Safety through Modeling Accident Risk Assessment of Runway. *Int. J. Environ. Res. Public Health* **2020**, *17*, 6085. [CrossRef]
58. Ayres, M.; Shirazi, H.; Carvalho, R.; Hall, J.; Speir, R.; Arambula, E.; David, R.; Gadzinski, J.; Caves, R.; Wong, D.; et al. Modelling the location and consequences of aircraft accidents. *Saf. Sci.* **2013**, *51*, 178–186. [CrossRef]
59. Federal Aviation Administration. *Airport Design Advisory Circular*; FAA AC 150/5300-13A; U.S. Department of Transportation, Federal Aviation Administration: Washington, DC, USA, 2014. Available online: https://www.faa.gov/documentLibrary/media/Advisory_Circular/150-5300-13A-chg1-interactive-201612.pdf (accessed on 25 August 2024).
60. Pinto Moreno, D. Le Aree di Sicurezza Nei Territori Limitrofi Agli Aeroporti: Confronto Fra i Metodi di Valutazione del Rischio E.N.A.C. e F.A.A. Master's Thesis, La Sapienza, Università di Roma, Rome, Italy, 2020. (In Italian).
61. Airport Cooperative Research Program. *Development of a Runway Veer-Off Location Distribution Risk Assessment Model and Reporting Template*; ACRP Report 107; The National Academies Press: Washington, DC, USA, 2014.
62. Bills, K.; Costello, L.; Cattani, M. Major aviation accident investigation methodologies used by ITSA members. *Saf. Sci.* **2023**, *168*, 106315. [CrossRef]
63. Amaral, Y.; Santos, L.F.F.M.; Valério, D.; Melicio, R.; Barqueira, A. Probabilistic and statistical analysis of aviation accidents. *J. Phys. Conf. Ser.* **2023**, *2526*, 012107. [CrossRef]
64. Moretti, L.; Di Mascio, P.; Nichele, S.; Cokorilo, O. Runway veer-off accidents: Quantitative risk assessment and risk reduction measures. *Saf. Sci.* **2018**, *104*, 157–163. [CrossRef]
65. Moretti, L.; Cantisani, G.; Caro, S. Airport veer-off risk assessment: An Italian case study. *ARPN J. Eng. Appl. Sci.* **2017**, *12*, 900–912.
66. Moretti, L.; Cantisani, G.; Di Mascio, P.; Nichele, S. A runway veer-off risk assessment based on frequency model: Part I. probability analysis. In Proceedings of the International Congress on Transport Infrastructure and Systems, Rome, Italy, 10–12 April 2017.
67. Pothana, P.; Thornby, J.; Ullrich, M.; Vidhyadharan, S.; Snyder, P. *UAS Risk Analysis in and Around Airports*; Petroleum Engineering Posters and Presentations; University of North Dakota: Grand Forks, ND, USA, 2023; Volume 7, Available online: https://commons.und.edu/pe-pp/7 (accessed on 13 November 2024).
68. Štumper, M.; Kraus, J.; Vittek, P.; Lališ, A. Runway safety areas. *MAD Mag. Aviat. Dev.* **2015**, *3*, 5–8. [CrossRef]
69. Szabo, S.; Vittek, P.; Kraus, J.; Plos, V.; Lališ, A.; Štumper, M.; Vajdová, I. Probabilistic model for airport runway safety areas. *Transp. Probl.* **2017**, *12*, 89–97. [CrossRef]
70. Barry, D.J. Estimating runway veer-off risk using a Bayesian network with flight data. *Transp. Res. Part C Emerg. Technol.* **2021**, *128*, 103180. [CrossRef]
71. Kitson, N.K.; Constantinou, A.C.; Guo, Z.; Liu, Y.; Chobtham, K. A survey of Bayesian Network structure learning. *Artif. Intell. Rev.* **2023**, *56*, 8721–8814. [CrossRef]
72. Koller, D.; Friedman, N. *Probabilistic Graphical Models: Principles and Techniques*, 1st ed.; The MIT Press: Cambridge, UK, 2011.
73. Fenton, N.; Neil, M. *Risk Assessment and Decision Analysis with Bayesian Networks*; CRC Press: Boca Raton, FL, USA, 2013.
74. Stolyarov, V.V.; Jamal-Eddine, A. Risk Assessment of Aircraft's Lateral Veer-Off the Runway Surface during Landing. *Open J. Appl. Sci.* **2023**, *13*, 1246–1256. [CrossRef]
75. Poisson, S.D. Mémoire sur l'équilibre et le mouvement des corps élastiques. *Mém. Acad. R. Sci. Inst. Fr.* **1829**, *8*, 357–570.
76. Ketabdari, M.; Giustozzi, F.; Crispino, M. Sensitivity analysis of influencing factors in probabilistic risk assessment for airports. *Saf. Sci.* **2018**, *107*, 173–187. [CrossRef]
77. Post, J.A. *Identification and Analysis of Veer Off Risk Factors in Accidents/Incidents*; NLR: Amsterdam, The Netherlands, 2015.
78. Lee, Y. Causal factors analysis of runway excursion occurrences through fuzzy logic modeling method. *Transp. Eng.* **2023**, *14*, 100204. [CrossRef]
79. Galagedera, S.; Pasindu, H.; Adikariwattage, V. Evaluation of the impact of runway characteristics on veer-off risk at rapid exit taxiways. *Transp. Res. Interdiscip. Perspect.* **2021**, *12*, 100480. [CrossRef]
80. Galagedera, S.; Adikariwattage, V.; Pasindu, H.R. Evaluation of rapid exit locations based on veer-off risk for landing aircraft. *Sustainability* **2021**, *13*, 5134. [CrossRef]
81. Yang, Y.; Zhu, X.; Jelagin, D.; Guarin, A.; Ong, G.P. Numerical analysis of hydroplaning and veer-off risk of dual-tyre on a wet runway. *Int. J. Pavement Eng.* **2023**, *24*, 2229479. [CrossRef]
82. Sivakumar, S. A novel integrated risk management method for airport operations. *J. Air Transp. Manag.* **2022**, *105*, 102296. [CrossRef]
83. Distefano, N.; Leonardi, S. Risk assessment procedure for civil airports. *Int. J. Traffic Transp. Eng.* **2014**, *4*, 62–75. [CrossRef]
84. Di Mascio, P.; Cosciotti, M.; Fusco, R.; Moretti, L. Runway Veer-Off Risk Analysis: An International Airport Case Study. *Sustainability* **2020**, *12*, 9360. [CrossRef]
85. Li, C.; Phun, V.K.; Suzuki, M.; Yai, T. The Effects of Aviation Accidents on Public Perception toward an Airline. *J. East. Asia Soc. Transp. Stud.* **2015**, *11*, 2347–2362. [CrossRef]
86. Halawi, L.; Miller, M.; Holley, S. *Beyond the Blue Skies: A Comprehensive Guide for Risk Assessment in Aviation*; IntechOpen: London, UK, 2024. [CrossRef]
87. Blom, H.A.; Jiang, C.; Grimme, W.B.; Mitici, M.; Cheung, Y.S. Third party risk modelling of Unmanned Aircraft System operations, with application to parcel delivery service. *Reliab. Eng. Syst. Saf.* **2021**, *214*, 107788. [CrossRef]

88. Đorem, M.S.; Netjasov, F.T. Third party risk modelling in surrounding of Airport Nikola Tesla in Belgrade. *Tehnika* **2018**, *73*, 549–556. [CrossRef]
89. Kim, S.H. Third-Party Risk Analysis of Small Unmanned Aircraft Systems Operations. *J. Aerosp. Inf. Syst.* **2020**, *17*, 24–35. [CrossRef]
90. Hong, S.-B.; Dilshod, T.; Kim, D. An Application of the Risk Assessment Model for Runway End Safety Areas to a Specific Airport in Korea. *Int. J. Control. Autom.* **2016**, *9*, 287–298. [CrossRef]