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A Study on the Risk Probability of Risk Mitigation Alternatives at Non-Compliance Airport with Runway Strip Criteria

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Abstract

A runway strip is defined as the surface surrounding a runway established or suitable for reducing the risk of damage to aircraft in the event of a runway excursion. This study aims to implement the RSARA and LRSARA models at an airport not meeting the runway strip dimension criteria required by standards for aerodrome physical characteristics. The airport is considering alternatives to secure the runway strip criteria such as the displaced threshold and runway length extension, which is predicted to reduce the runway excursion probability. As the results of this study, it was discovered that the risk probability increases with the increases of the displaced runway distance due to relatively reduced runway length. Therefore, a reduced runway length to meet runway strip criteria may not be the most effective risk mitigation alternative, and it should be acknowledged that such a strategy can harm aviation Safety.

Keywords: runway strip, runway excursion, runway displaced threshold, risk probability, risk mitigation alternative

1. Introduction

A runway strip is a safety zone installed around a runway to reduce the risk of damage to aircraft and passengers in the event of an excursion from the runway during takeoff and landing [1]. It refers to the rectangular-shaped land surface or water surface at the center line of the runway, the dimensions of which are determined by law and regulations in accordance with the International Civil Aviation Organization (ICAO) aerodrome reference code [2-3]. The Federal Aviation Administration (FAA)-mandated runway safety area (RSA) is a specific area surrounding the runway [4] that serves the same purpose as the runway strip, namely to reduce the damage caused to the aircraft in the event of an excursion from the runway during takeoff and landing.

According to worldwide aviation accident statistics from 2010 to 2020 [5], 67% of fatal accidents occurred during the aircraft takeoff and landing phase (takeoff/initial climb phase and final approach/landing phase), which caused 48% of the total fatalities. The causes of fatal accidents include loss of flight control, controlled flight into terrain (CFIT), system failure, and excursion from the runway. Risk factors such as human error significantly contribute to the cause of such accidents. However, the physical environment of the aerodrome, including the runway dimensions, is also a significant risk factor influencing the probability and severity of accidents [5].

A runway excursion is a veer-off, overrun, or undershoot from the runway surface while an aircraft is taking off or landing. It involves many factors ranging from unstable approaches to the condition of the runway. All parties involved (pilots, air traffic controllers, airport operators, etc.) must work together to mitigate the hazards that result in a runway excursion [6]. The most important and well-known risk evaluation studies for runway safety areas are the Airport Cooperative Research Program (ACRP) reports. Ayres Jr et al. [7] adopted the parameters through ACRP projects modeling the location and consequences of

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aircraft accidents. Szabo et al. [8] offered the general size of runway safety areas based on data from the ACRP Report 50. In addition, Moretti et al. [9] presented a quantitative risk assessment method to calculate the current level of risk for different runway codes and types of movement. Mascio et al. [10] also suggested a methodology for the quantitative risk assessment of runway veer-off, which presented a risk map that allows identifying the areas in the runway strip with the highest risk of a veer-off accident.

The Civil Aviation Authority (CAA) of New Zealand notified the W airport operator in 2017 that the runway end safety area (RESA) did not meet the aerodrome design standards (90 m × 90 m) as the dimensions were only 45 m from the Runway 34 threshold and 52 m from the Runway 16 threshold [11]. As a result, the W airport operator permanently displaced the threshold of Runway 34 and Runway 16 in 2019 to conform to the RESA requirements. It was determined that the runway excursion risk due to the airport's physical environmental factors could be reduced to an acceptable risk level by meeting the RESA-related airport design standards, i.e., by operating a 2,081 m × 45 m runway for A350-900 aircraft. In addition to W airport in New Zealand, numerous airports around the world, including S airport in London, UK, and B airport in Toronto, Canada, have had their thresholds displaced or runways extended to meet the RSA requirements.

The purpose of this study is to implement the runway safety area risk assessment (RSARA) and lateral RSARA (LRSARA) models at an airport in Korea. The case airport fails to meet the runway strip criteria required by domestic and international aerodrome design standards. The case airport operator is reviewing how to alleviate the risk of the case airport to an acceptable level through risk mitigation alternatives, such as displacing the threshold as in the case of W airport. Through quantitative risk analysis, this study aims to confirm whether the method of meeting facility standards by displacing the threshold has a positive impact on mitigating risk probability. In addition, based on the results of the risk analysis, the study aims to propose an optimal method for replacing the alternative of displacing the runway threshold.

2. Risk Assessment Model for Runway Strip

In Korea, the runway strip dimensions specified in ICAO Annex 14 (Aerodromes) are uniformly applied. In accordance with the fourteenth revision of ICAO Annex 14 in 2018, the width of the runway strip was partially reduced, and in November 2018, the standards for the design of aerodromes in Korea were revised to apply the same runway strip regulations as those in Annex 14. As shown in Fig. 1, for runway strips for which instrument approach procedures have been established with an aerodrome reference code number of “4” (airplane reference field length of 1,800 m or more), the length must extend at least 60 m from the runway threshold or the end of the runway (the end of the stop-way if there is a stop-way), and the width should be at least 140 m from the longitudinal centreline of the runway to the long side of the runway strip [12].

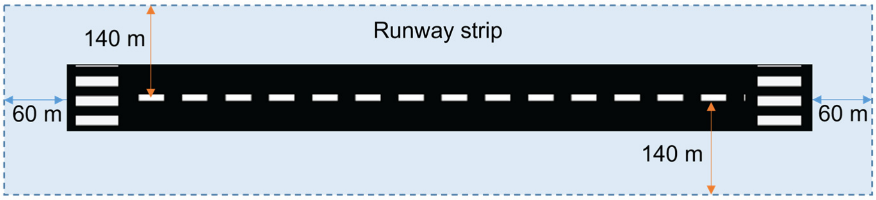


Fig. 1 Instrument runway strip for code number 3 or 4

This study considered the risk assessment models for runway safety areas: RSARA and LRSARA. These models include independent variables such as airport elevation, runway length, aircraft type, weather, and so on, which can well reflect data on the physical characteristics and flight operational characteristics of the airport. The model for risk assessment of RSA [13] is a quantitative risk assessment method developed in 2008 with FAA support as part of the ACRP. It is a probabilistic risk assessment model that evaluates the risk level for aircraft that undershoot or overrun the runway using scientific data and statistical theory. The model was developed based on the aircraft accident/incident data reports (ADREP) for major runway excursions that occurred in the RSA from 1982 to 2006, taking into account pertinent risk factors.

The improved model for risk assessment of RSA [14] is an improved version of the previous RSA risk assessment model, which is published as the ACRP Report 50 in 2011. This model was developed using data on major runway excursion-related accidents that occurred on RSA from 1982 to 2009. The existing RSA risk assessment model has difficulty in assessing the risk of runway veer-off. However, the LRSA model [15] presented in ACRP Report 107 solved this problem. Based on historical flight operational data and weather data, both models enable the estimation of the risk probability and severity of the aircraft operating in the current or planned RSA dimension [16].

The RSA and LRSA risk assessment models consist of three functions. First, event probability is a function depending on the operation condition, including aircraft characteristics/performance and weather conditions. Second, the aircraft location probability is a function estimating the excursion fraction of locations exceeding the given distance from the runway end or threshold, and third, the consequence is a function related to the nature and location of existing obstacles, as well as the type and size of an aircraft [13, 17]. The risk level is ultimately evaluated based on the aforementioned three functions, and this study was conducted with an emphasis on the event probability.

The basic event probability model structure selected is a logistic equation, as shown below:

$$P(Accident\ Occurence) = \frac{1}{1+e^{b_0+b_1x_1+b_2x_2+b_3x_3+\cdots+b_nx_n}} \tag{1}$$

where P is accident occurrence, the probability (0-100%) of an event occurring given certain operational conditions, x_i is an independent variable (e.g., aircraft type, ceiling, visibility, crosswind, temperature, precipitation, and log criticality factor), and b_i is a regression coefficient [18].

2.1. Longitudinal runway excursion risk probability model

The improved model for risk assessment of RSA (ACRP Report 50) expanded on the research presented in ACRP Report 3 to include the analysis of aircraft veer-offs, the use of declared distance, and additional variables such as tailwind, frozen precipitation, gust, etc. Compared to the previous model, the classification of user class and cloud height has been subdivided in the improved model, and the coefficient values of independent variables have been adjusted overall. The predictor variables were entered by blocks, each consisting of related factors, such that the change in the model's substantive significance could be observed as the variables were included [14]. Table 1 summarizes the model coefficients obtained for landing overrun (LDOR), landing undershoot (LDUS), landing veer-off (LDVO), take-off overrun (TOOR), and take-off veer-off (TOVO) [8].

Table 1 Independent variables used for risk probability models [14]

Variable	LDOR	LDUS	LDVO	TOOR	TOVO
Adjusted constant	-13.065	-15.378	-13.088	-14.293	-15.612
User class F		1.693		1.266	
User class G	1.539	1.288	1.682		2.094
User class T/C	-0.498	0.017			
Aircraft class A/B	-1.013	-0.778	-0.770	-1.150	-0.852
Aircraft class D/E/F	0.935	0.138	-0.252	-2.108	-0.091
Ceiling less than 200 ft	-0.019	0.070		0.792	
Ceiling 200 to 1000 ft	-0.772	-1.144		-0.114	
Ceiling 1000 to 2500 ft	-0.345	-0.721			
Visibility less than 2 SM	2.881	3.096	2.143	1.364	2.042
Visibility from 2 to 4 SM	1.532	1.824		-0.334	0.808
Visibility from 4 to 8 SM	0.200	0.416		0.652	-1.500
Crosswind from 5 to 12 kt	-0.913	-0.295	0.653	-0.695	0.102
Crosswind from 2 to 5 kt	-1.342	-0.698	-0.091	-1.045	
Crosswind more than 12 kt	-0.921	-1.166	2.192	0.219	0.706
Tailwind from 5 to 12 kt			0.066		
Tailwind more than 12 kt	0.786		0.98		

Table 1 Independent variables used for risk probability models [14] (continued)

Variable	LDOR	LDUS	LDVO	TOOR	TOVO
Temp less than 5°C	0.043	0.197	0.558	0.269	0.988
Temp from 5 to 15°C	-0.019	-0.71	-0.453	-0.544	-0.42
Temp more than 25°C	-1.067	-0.463	0.291	0.315	-0.921
Icing conditions	2.007	2.703	2.67	3.324	
Rain		0.991	-0.126	0.355	-1.541
Snow	0.449	-0.25	0.548	0.721	0.963
Frozen precipitation			-0.103		
Gusts		0.041	-0.036	0.006	
Fog			1.74		
Thunderstorm	-1.344				
Turboprop			-2.517	0.56	1.522
Foreign OD	0.929	1.354	-0.334		-0.236
Hub/non-hub airport	1.334				-0.692
Log criticality factor	9.237	1.629	4.318		1.707
Night conditions			-1.36		

Where:

Equipment class	C	Large jet of MTOW 41k-255k lb (A320, B737, etc.)
Heavy aircraft	AB	Heavy jets of MTOW 255k lb+ (A340, B777, etc.)
Commuter aircraft	D	Large commuter of MTOW 41k-255k lb (ERJ-190, CRJ-900, Regional Jets, ATR42, etc.)
Medium aircraft	E	Medium aircraft of MTOW 12.5k-41k lb (Business jets, Embraer 120, Learjet 35, etc.)
Small aircraft	F	Small aircraft of MTOW 12.5k or less (Beech-90, Cessna Caravan, etc.)
User class	C: Commercial, F: Cargo, T/C: Taxi/Commuter, G: General Aviation	
Foreign OD	Foreign origin/destination (yes/no) - Ref: domestic	
Ceiling (feet)	Ref: Ceiling height > 2500 ft	
Visibility (status miles)	Ref: Visibility > 8 SM	
Crosswind (knot)	Ref: Crosswind < 2 kt	
Tailwind (knot)	Ref: Tailwind < 5 kt	
Gusts (knot)	Ref: No gusts	
Thunderstorms (yes/no)	Ref: No thunderstorms	
Icing conditions (yes/no)	Ref: No icing conditions	
Snow (yes/no)	Ref: No snow	
Rain (yes/no)	Ref: No rain	
Fog (yes/no)	Ref: No fog	
Air temperature (°C)	Ref: Air temperature above 15°C and below 25°C	
Non-hub airport (yes/no)	Ref: Hub airport	
Log criticality factor	If Log (CF) > 0, the available runway distance is smaller than the required distance	

Notes:
Ref: indicates the reference category against which the odds ratios should be interpreted.
Non-hub airport: airport having less than 0.05% of annual passenger boarding

Fig. 2 shows the axis locations used to represent the type of overrun. x represents the distance beyond the end of the runway along the extended runway centerline [7], and y represents the distance of deviation from the extended runway centreline to the edge of the runway. The reference location of the aircraft is its nose wheel. The x-y origin for overrun is the centreline at the runway threshold and the y-axis origin for veer-off is the lateral edge of the runway. The location probability model for the runway excursion position of the aircraft beyond the distance of x and y is presented in Table 2. To model the reported runway excursion-related accident data, these functions comprise a standardized model created by adding the weights of unreported incidents to the raw one.

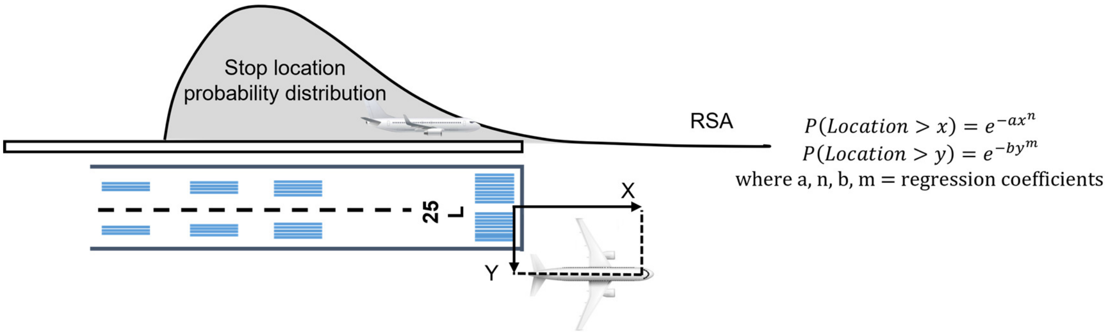


Fig. 2 Concept for aircraft overrun model

Table 2 Location models for the type of events [14]

Type of events	Axis	Location model	R^2 (%)
LDOR	X	$P(d > x) = e^{-0.00321x^{0.984941}}$	99.8
	Y	$P(d > y) = e^{-0.20983y^{0.4862}}$	93.9
LDUS	X	$P(d > x) = e^{-0.01481x^{0.751499}}$	98.7
	Y	$P(d > y) = e^{-0.02159y^{0.773896}}$	98.6
LDVO	Y	$P(d > y) = e^{-0.02568y^{0.803946}}$	99.5
TOOR	X	$P(d > x) = e^{-0.00109x^{1.06764}}$	99.2
	Y	$P(d > y) = e^{-0.04282y^{0.659566}}$	98.7
TOVO	Y	$P(d > y) = e^{-0.01639y^{0.863461}}$	94.2

For Table 2, the parameters represented that d is any given distance of interest, x is the longitudinal distance from the runway threshold, $P(d > x)$ is the probability the wreckage location exceeds distance x from the runway threshold, y is the transverse distance from the extended runway centreline (overruns and undershoots) or from the runway edge (veer-off), and $P(d > y)$ is the probability the wreckage location exceeds distance y from the extended runway centreline (overruns and undershoots) or from the runway edge (veer-off) [14].

2.2. Lateral runway excursion risk probability model

The LRSA Program of ACRP Report 107, which was published in 2014, newly established the veer-off model that could not be evaluated in the existing model by analyzing the runway excursion-related accident data. For the risk probability model, the LDVO constant b model is defined as

$$\begin{aligned} b = {} & \text{-}13.088 + 1.682(User\ \text{Class G}) - 0.770(Aircraft\ Class\ A/B) - 0.252(Aircraft\ Class\ D/E/F) \\ & + 2.143(Visibility < 2\ SM) - 0.091(Crosswind\ 2\ to\ 5\ kt) + 0.653(Crosswind\ 5\ to\ 12\ kt) \\ & + 2.192(Crosswind > 12\ kt) + 0.066(Tailwind\ 5\ to\ 12\ kt) + 0.980(Tailwind > 12\ kt) \\ & + 0.558(Temp < 5^\circ C) - 0.453(Temp\ 5\ to\ 15^\circ C) + 0.291(Temp > 25^\circ C) \\ & + 2.670(Icing\ Condition) - 0.126(Rain) + 0.548(Snow) - 0.103(Frozen\ Precipitation) \\ & - 0.036(Gusts) + 1.740(Fog) - 2.517(Turboprop) - 0.334(Foreign\ OD) \\ & + 4.318(Log\ Criricality\ Factor) - 0.360(Night\ Conditions) \end{aligned} \tag{2}$$

and the takeoff veer-off (TOVO) constant b model is defined as

$$\begin{aligned} b = {} & \text{-}15.612 + 2.094(User\ \text{Class G}) - 0.852(Aircraft\ Class\ A/B) - 0.091(Aircraft\ Class\ D/E/F) \\ & + 2.042(Visibility < 2\ SM) + 0.808(Visibility\ 2\ to\ 4\ SM) - 1.500(Visibility\ 4\ to\ 8\ SM) \\ & + 0.102(Crosswind\ 5\ to\ 12\ kt) + 0.706(Crosswind > 12\ kt) + 0.988(Temp < 5^\circ C) \\ & - 0.420(Temp\ 5\ to\ 15^\circ C) - 0.921(Temp > 25^\circ C) - 1.541(Rain) + 0.963(Snow) \\ & + 1.522(Tueboprop) - 0.236(Frozen\ OD) - 0.692(Non-Hub\ Airport) \\ & + 1.707(Log\ Criricality\ Factor) \end{aligned} \tag{3}$$

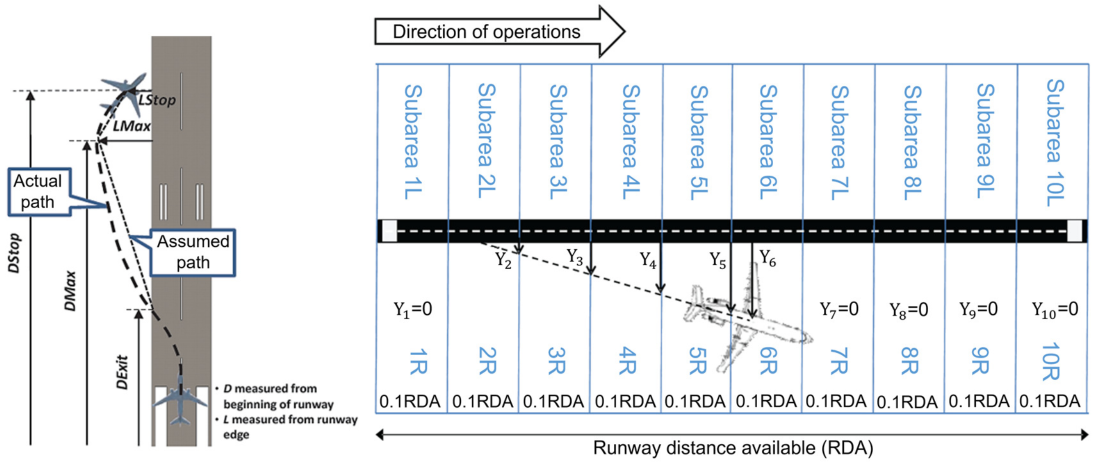


Fig. 3 Concept of veer-off model [15]

The aircraft veer-off path refers to the path of the aircraft from the point where the aircraft deviates from the edge of the runway to the point the aircraft comes to a stop or reenters the runway (see Fig. 3). In Fig. 3, DExit is defined as the longitudinal distance measured from the beginning of the runway to the point where the aircraft departed from the runway edge, and DStop is the longitudinal distance measured from the beginning of the runway to the point where the aircraft stopped or returned to the runway [15].

The LRSA location model divides the runway into 10 sections of equal length, each of which includes both the right and the left side subareas of the lateral runway area, and models the probability that the lateral deviation L exceeds a given distance Li within a predetermined subarea between DExit and DStop from the edge of the runway. The probability that the lateral excursion veer-off L exceeds the specified distance L_i when the aircraft deviates from the runway in each subregion of the runway can be indicated as

$$P = e^{aLb}, \; for \; L > L_i \tag{4}$$

where a and b are model coefficients. And Table 3 provides a summary of the regression coefficients and R^2 values (R^2, which represents the excellent accuracy achieved) for the bottom 10 sections of the runway based on the veer-off location probability model.

Table 3 Lateral deviation models for normalization

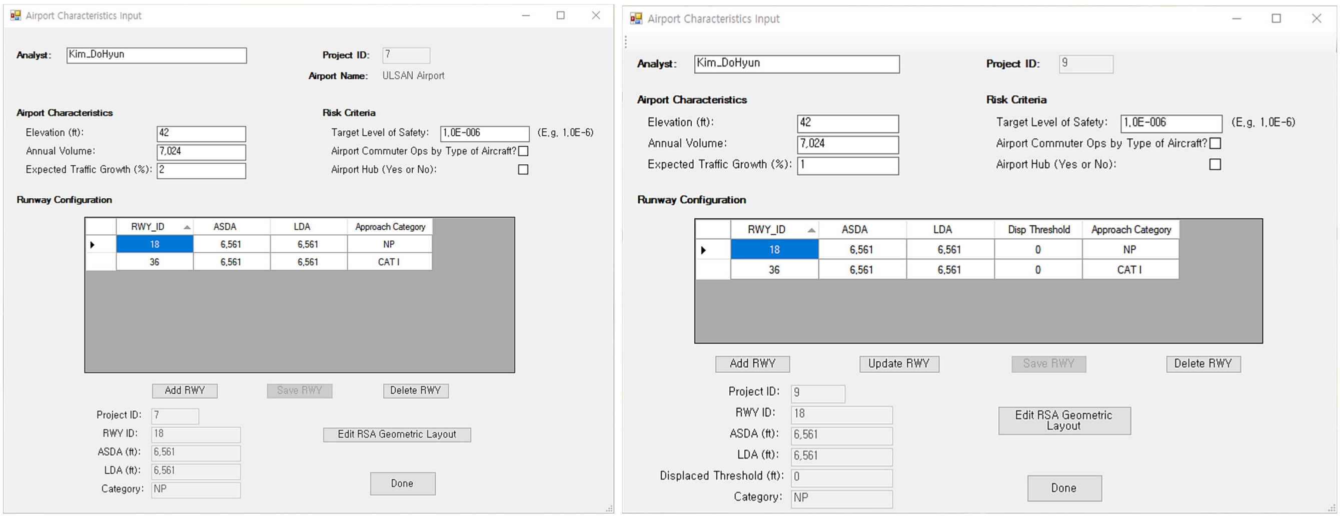
Runway subarea	L range	a	b	R^2 (%)
1	0-0.1	-0.03399	0.8407	97.4
2	0.1-0.2	-0.00690	1.1339	99.3
3	0.2-0.3	-0.01306	1.0032	99.4
4	0.3-0.4	-0.00644	1.1576	99.5
5	0.4-0.5	-0.01354	0.9881	99.1
6	0.5-0.6	-0.00906	1.0482	98.3
7	0.6-0.7	-0.00909	1.0014	99.0
8	0.7-0.8	-0.01136	0.9206	99.2
9	0.8-0.9	-0.01037	0.970348	98.9
10	0.9-1.0	-0.00361	1.18109	99.1

3. Application of Risk Estimation Model

This study analyzed a case airport in the Republic of Korea that did not meet the required standard for runway strips, as stipulated by law and regulations. The airport is categorized by ICAO aerodrome reference code number “4” and code letter

"C". For the RSARA and LRSARA programs to estimate the risk probability of the runway strip, data on the general characteristics of the case airport (including physical properties), flight operations performance data, and meteorological data are required. Based on statistical data from domestic airport operators and the Aviation Meteorological Office, flight performance data were collected for the period between January 1 and December 31, 2019, before the COVID-19 pandemic, which severely affected the air transportation industry. The 2022 Aeronautical Information Publication (AIP) was consulted for data on the general characteristics of the case airport. Aircraft specifications and RSA model parameters are provided by the RSA Analysis programs (RSARA V.2 and LRSARA).

3.1. General characteristics data input



Analyst: Kim_DoHyun
Project ID: 7
Airport Name: ULSAN Airport

Airport Characteristics
Elevation (ft): 42
Annual Volume: 7,024
Expected Traffic Growth (%): 2

Risk Criteria
Target Level of Safety: 1,0E-006 (E.g. 1,0E-6)
Airport Commuter Ops by Type of Aircraft? ☐
Airport Hub (Yes or No): ☐

Runway Configuration

RWY_ID	ASDA	LDA	Approach Category
18	6,561	6,561	NP
36	6,561	6,561	CAT I

Project ID: 7
RWY ID: 18
ASDA (ft): 6,561
LDA (ft): 6,561
Category: NP

Analyst: Kim_DoHyun
Project ID: 9

Airport Characteristics
Elevation (ft): 42
Annual Volume: 7,024
Expected Traffic Growth (%): 1

Risk Criteria
Target Level of Safety: 1,0E-006 (E.g. 1,0E-6)
Airport Commuter Ops by Type of Aircraft? ☐
Airport Hub (Yes or No): ☐

Runway Configuration

RWY_ID	ASDA	LDA	Disp Threshold	Approach Category
18	6,561	6,561	0	NP
36	6,561	6,561	0	CAT I

Project ID: 9
RWY ID: 18
ASDA (ft): 6,561
LDA (ft): 6,561
Displaced Threshold (ft): 0
Category: NP

Fig. 4 Airport characteristics input screens of RSARA and LRSARA program

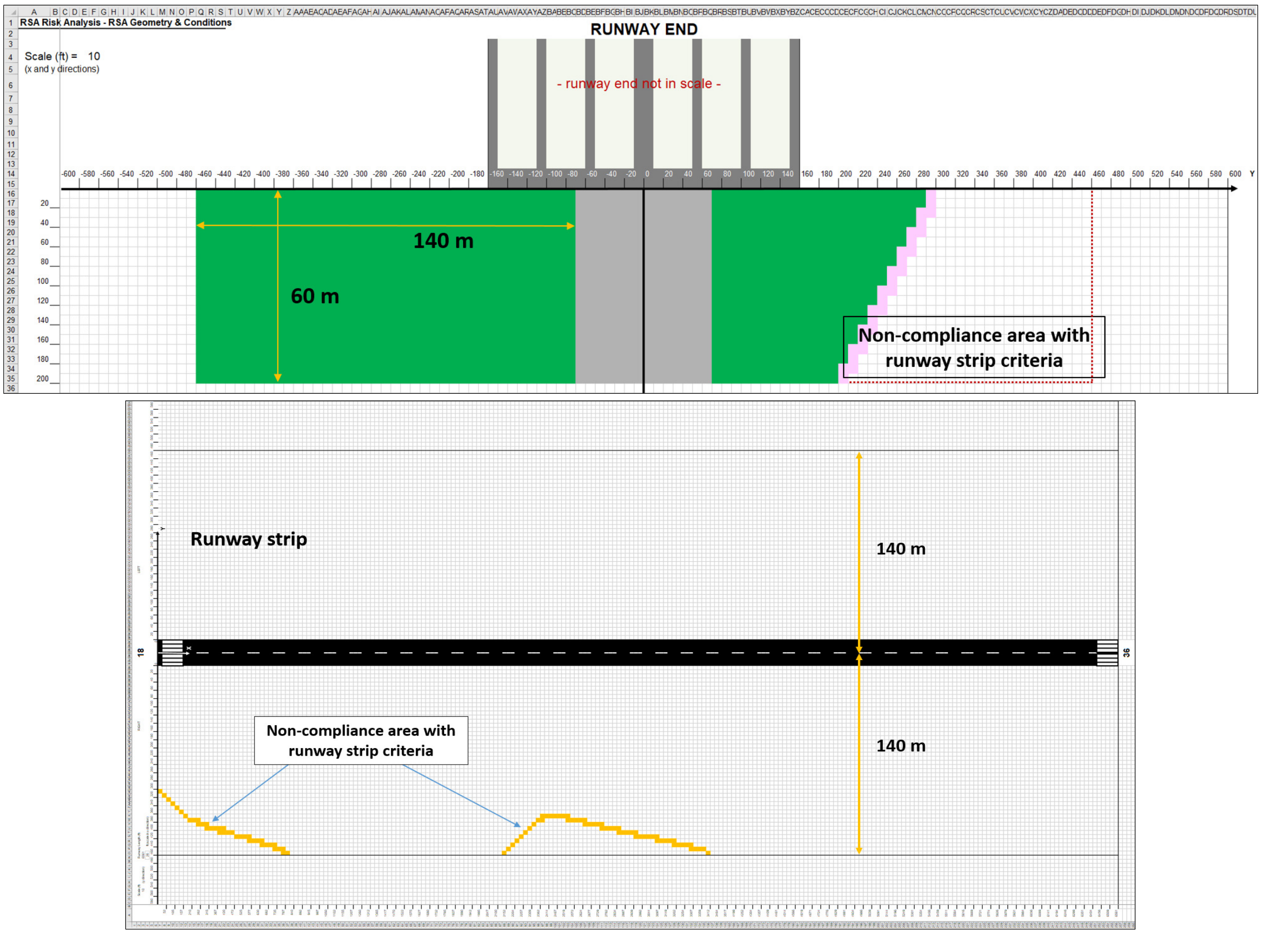
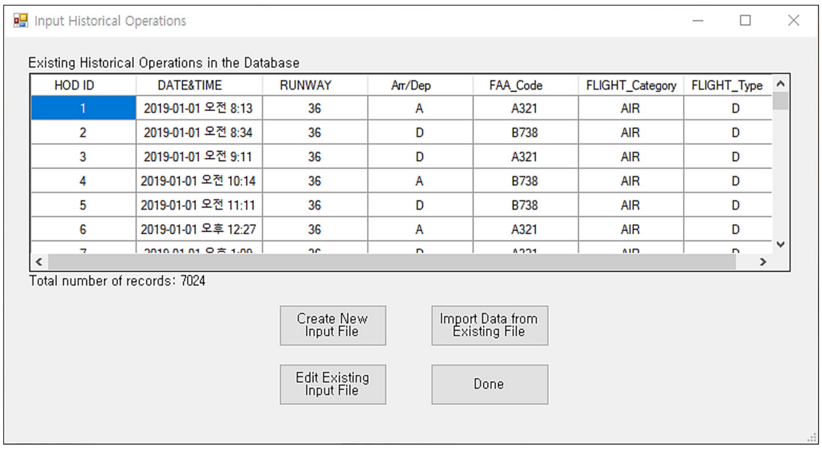


Fig. 5 Runway strip layout of the case airport

The general characteristics data of the case airport, including the number of flights (7,024 in 2019), the expected traffic growth (1.0%), airport elevation (42 ft; 4.8 m), runway direction (18, 36), declared distance (including landing distance available (LDA)), and approach category (Runway 18; non-precision approach, Runway 36; ILS CAT I) were inputted (see Fig. 4). The runway strip layout of the case airport was entered to the programs based on a CAD file and satellite data provided by the airport operator. As shown in Fig. 5, a part of the runway strip in the direction of Runway 18 at the case airport does not meet the Korean regulations for the width of runway strips (more than 140 m from the centerline of the runway).

3.2. Flight data and weather data input

The number of flights in 2019 at the case airport, which is a domestic airport, stood at 7,024 (departures and arrivals; 3,512 each) (see Fig. 6). The fleet consisted of B737-800/900 (3,594 flights), A321 (3,146 flights), ATR-72 (282 flights), and additional Gulfstream aircraft (2 flights). The use ratio of Runway 36 and 18 directions came to 81.5:18.5, and the Runway 36 direction, which requires attention to overrunning (LDOR and TOOR) during take-off and landing, was primarily used.



Existing Historical Operations in the Database

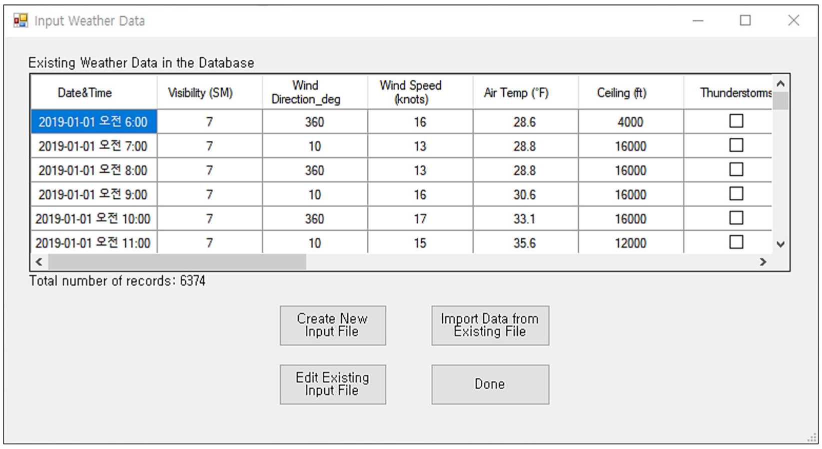
HOD ID	DATE&TIME	RUNWAY	Arr/Dep	FAA_Code	FLIGHT_Category	FLIGHT_Type
1	2019-01-01 오전 8:13	36	A	A321	AIR	D
2	2019-01-01 오전 8:34	36	D	B738	AIR	D
3	2019-01-01 오전 9:11	36	D	A321	AIR	D
4	2019-01-01 오전 10:14	36	A	B738	AIR	D
5	2019-01-01 오전 11:11	36	D	B738	AIR	D
6	2019-01-01 오후 12:27	36	A	A321	AIR	D

Total number of records: 7024

Fig. 6 Input data of historical flight operation (2019)

According to the airport operator, there were a total of 192 flight cancellations at the case airport in 2019. The causes were determined to be attributable to bad weather (visibility, crosswind, snow, ceiling height, etc.) in 85% of the cases, aircraft connections in 14%, and other (aircraft maintenance, etc.) in 1% of the cases.

As for meteorological data, 8,759 hourly weather data were obtained from the open MET data portal of the Aviation Meteorological Office between 00:00 on January 1, 2019, and 23:00 on December 31, 2019, and 6,374 of these measurements were used for analysis. Visibility, wind component, temperature, ceiling height, thunderstorm, precipitation, fog, etc. are among the meteorological data items utilized by the RSARA and LRSARA Programs (see Fig. 7), and precipitation data is subdivided into snow and rain.



Existing Weather Data in the Database

Date&Time	Visibility (SM)	Wind Direction_deg	Wind Speed (knots)	Air Temp (°F)	Ceiling (ft)	Thunderstorms
2019-01-01 오전 6:00	7	360	16	28.6	4000	☐
2019-01-01 오전 7:00	7	10	13	28.8	16000	☐
2019-01-01 오전 8:00	7	360	13	28.8	16000	☐
2019-01-01 오전 9:00	7	10	16	30.6	16000	☐
2019-01-01 오전 10:00	7	360	17	33.1	16000	☐
2019-01-01 오전 11:00	7	10	15	35.6	12000	☐

Total number of records: 6374

Fig. 7 Input of weather data (2019.1.1-2019.12.31)

Among 6,374 data excluding non-operating hours (00:00-05:00) having no measurement data, the number of data on visibility with 2 SM or below was found to be 159 (2.4%), while that between 2 SM and 4 SM, and 4 SM or above were found to be 767 (12.0%) and 5,448 (62.5%), respectively. For crosswind and tailwind, each program analyzes the wind component based on the direction of the runway and automatically calculates the velocity and direction of the crosswind. When analyzing only the wind speed data at the case airport, it was found that there were 2,552 data with wind speeds below 5 knots and 3,248 with wind speeds between 5 and 12 knots.

4. Results of Estimating Risk Probability

4.1. Results of runway strip risk probability

Target level of safety (TLS) is the degree to which safety is to be pursued in a given context, assessed with reference to an acceptable or tolerable risk [10]. Table 4 displays the outcomes of analyzing the risk probability of the runway strip with the RSARA and LRSARA programs upon setting the TLS of the case airport to 1.0E-06.

As a result of the analysis, the average risk probability was determined to be 3.3E-07, which was lower than the TLS, but approximately 1.0E-08 higher than the probability of risk probability when the runway strip criteria were met (LRSARA runway edge). Based on the number of flights in 2019, the average number of years for critical incidents was greater than once every 100 years. In 2019, 7.0% of aircraft operations at the case airport exceeded the TLS, which is 0.8% more than when the runway strip criteria were met (see Table 4).

Table 4 Risk probabilities result for the runway strip of case airport

LRSARA (runway edge)	Average risk of accident	Average number of years to critical incident	% operations above TLS	Average number of years to critical incident for TLS
LDVO	6.4E-07	>100	13.8	>100
TOVO	1.7E-08	>100	0.1	>100
Total (case airport)	3.3E-07	>100	7.0	89
Standard strip	3.2E-07	>100	6.2	89

RSARA (beyond threshold)	Average risk of accident	Average number of years to critical incident	% operations above TLS	Average number of years to critical incident for TLS
LDOR	3.3E-06	63	59.0	>100
TOOR	5.8E-07	>100	14.9	>100
LDUS	1.5E-07	>100	1.2	>100
LDVO	1.1E-07	>100	0.8	>100
TOVO	3.8E-09	>100	0.0	>100
Total	2.1E-06	53	38.0	89

Total runway strip risk probability	
Case airport	2.40E-06
When strip standards for dimensions are met	2.36E-06

The average risk probability of the runway strip at the case airport is 2.40E-06 (sum of RSARA and LRSARA risk probability), which corresponds to a risk probability of approximately 2.4 per million flights (approximately 89 years based on 7,024 flight operations in 2019 while assuming a 1% traffic growth at the case airport). If the case airport's runway strip complies with standard requirements, the total risk probability is 2.36E-06, and the difference from the risk probability of the existing runway strip dimensions is only 0.04E-06. Nonetheless, both the current risk probability of the case airport (2.40E-06) and the risk probability when the standards are met (2.36E-06) exceed the TLS (1.0E-06). To keep the risk probability at the case airport below the TLS, it is necessary to evaluate alternatives (e.g., changing the physical characteristics of the runway or the operation characteristics of the aircraft, etc.).

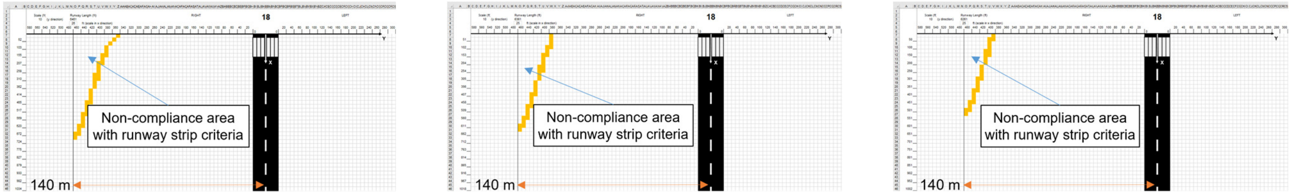
According to the analysis results by runway direction at the case airport, the LRSARA risk probability when approaching Runway 36 (3.3E-07) was greater than that of Runway 18 (3.0E-07), and the risk probability for overrun and undershoot of Runway 18 (1.9E-06) was greater than that of Runway 36 (5.5E-07) by 1.35E-06 (approximately 1.35 events per million flights) (see Table 5). This is the result of the runway strip criteria not being met at the threshold of Runway 18.

Table 5 Risk probabilities result by runway direction

Runway 18	Average risk of accident	% operations above TLS	Runway 36	Average risk of accident	% operations above TLS
LRSARA (veer-off at strip)	3.0E-07	8.7	LRSARA (veer-off at strip)	3.3E-07	6.6
RSARA (overrun/undershoot)	1.9E-06	34.1	RSARA (overrun/undershoot)	5.5E-07	11.2
RSARA (veer-off beyond threshold)	5.4E-08	0.2	RSARA (veer-off beyond threshold)	5.8E-08	0.4

4.2. *Displacing threshold of runway and change in risk probability*

As stated in the introduction section of the study, there are alternatives to displace the runway threshold to meet the runway strip criteria to the greatest extent possible. If the runway threshold is displaced permanently at the case airport, portions of the existing runway strip that do not meet facility standards can be reduced. However, due to the shorter runway length (6,561 ft), it is necessary to conduct a quantitative analysis of how the partial satisfaction of facility standards and the shorter runway length will affect the safe operation of aircraft in terms of risk probability.



(a) 30 m displaced threshold (b) 60 m displaced threshold (c) 90 m displaced threshold

Fig. 8 Runway 18 strip layout by displaced threshold

This study examines the variation in risk probability caused by relocating the airport's runway threshold by 30 m, 60 m, and 90 m, respectively (see Fig. 8). Based on 2019 aircraft operation and meteorological data of the case airport, the average risk probability that an aircraft must bear during takeoff or landing was calculated to be 2.36E-06 if the runway strip width criteria of 140 m from the runway centerline are met. On the other hand, the runway strip facilities at the case airport had a risk probability of 2.40E-06, which was 4.0E-08 greater than when the runway strip dimension standards are met.

Table 6 Risk probabilities result by displaced threshold: 30 m, 60 m, 90 m

Runway 18-36	Risk probability	Remarks
When the runway strip criteria are met	2.36E-06	-
Case airport	2.40E-06	Current runway strip layout
Displacing Runway 18 threshold by 30 m	2.50E-06	1.0E-07 increase
Displacing Runway 18 threshold by 60 m	2.62E-06	2.2E-07 increase
Displacing Runway 18 threshold by 90 m	2.75E-06	3.5E-07 increase

If the runway threshold is permanently displaced by 30 m, 60 m, or 90 m, the area that does not meet the runway strip standard will be reduced, but the runway length will be reduced from the current 6,561 ft by the displaced distance. Unlike the expectation that it will meet the legal standard of partially meeting runway strip criteria and that risk probability will be mitigated qualitatively, it was found that the risk probability increased by 1.0E-07, 2.2E-07, and 3.5E-07 by displacing 30 m, 60 m, and 90 m, respectively, as shown in the analysis results (Table 6). This means that if the runway length at an airport is similar to the take-off/landing distances in the specifications of aircraft operating in the case airport (B738, A321), displacing and reducing the runway to meet the runway strip criteria can harm aviation Safety. Therefore, it can be confirmed that simply meeting airport design standards by permanently displacing the runway threshold to contribute to the safe operation of aircraft may not be an appropriate risk mitigation alternative depending on airport operating conditions.

Due to the site conditions surrounding the case airport, there is limited space to expand the runway. This study examined the risk probability if the runway length at the case airport was extended to 2,300 m and 2,600 m by extending the runway length by 300 m (984 ft) and 600 m (1,968 ft) within the possible extension range. Using the same aircraft operation data as in 2019, the risk probability is reduced from 1.31E-06 to 1.09E-06 when the runway length of the case airport is extended by 300 m. In the case of extending the runway by 600 m to 2,600 ft, the risk probability was calculated to be 1.16E-06, which is 0.15E-06 less than in the case of extending the runway by 300 m (see Table 7).

Table 7 Risk probabilities result by runway extension: +984 ft, +1,968 ft

Runway 18-36	Risk probability	Remarks
Case airport	2.40E-06	Current runway strip layout
Extending runway length +300 m	1.31E-06	1.09E-06 reduction
Extending runway length +600 m	1.16E-06	1.24E-06 reduction
Switching all aircraft to ATR-72	1.12E-06	1.28E-06 reduction

If extending the runway at the case airport is impractical for various reasons, it is possible to reduce the aerodrome reference code number of the operating aircraft [1], which can have the same effect as a runway extension. As a result of analyzing the 2019 flight operations data by switching both B737-800/900 and A321 aircraft to ATR-72 aircraft, the risk probability was calculated to be 1.12E-06, which was reduced by more than half compared to the current risk probability at the case airport (see Table 7). In this case, even if the case airport runway strip is not physically improved to the standard dimensions, the risk probability is close to the TLS (1.0E-06), and it is confirmed that there would be a reduction in the risk probability.

5. Conclusions

For the safe operation of aircraft in the airport, domestic and international safety-related aviation authorities, including the ICAO, add requirements that must be met to the standards for the design of aerodromes. The standards also specify the dimensions of the runway strip to minimize the risk of damage to aircraft and passengers caused by runway excursions.

Using the RSA and LRSA risk assessment programs, this study estimated the probability of runway excursion-related risks for an airport that does not meet the standards for the design of aerodromes (runway strip dimensions) among airports in Korea. Based on the 2019 flight operation and weather data, the risk probability with the existing runway strip dimensions at the case airport, the risk probability when the runway strip criteria are met, and the risk probability of alternatives, i.e. the displacing runway threshold and the runway extension plans, were estimated.

As a result, it was determined that the risk probability associated with the runway strip at the case airport is 4.0E-08 greater than when the runway strip criteria are met. In the case of the permanent runway displaced threshold, it was discovered that the risk probability increases as the displaced runway distance increases (relatively reduced runway length). However, in the case of runway extension (applying the currently operating flight), the risk probability was discovered to reduce as the runway extension distance increased. The risk probability was also found to reduce in the case of changing the code number category of operating aircraft (from B737-800 class to ATR-72 class) in the current runway length.

Contrary to qualitative expectations, methods such as operating a reduced runway length to meet runway strip criteria may not be the most effective risk mitigation alternatives, and it should be acknowledged that such a strategy can have a negative impact on the safe operation of aircraft according to the findings of this study. Therefore, in the case of reviewing the alternatives to satisfy the runway strip criteria in accordance with the applicable regulations, it should be confirmed that the alternatives can effectively mitigate risk through quantitative risk assessment before its adoption.

Conflicts of Interest

The authors declare no conflict of interest.

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