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Evaluating the Installation of Arrestor Systems in Runway Safety Areas as a Measure of Overrun Risk Mitigation

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Abstract: The safety area is an important facility of runways that helps prevent severe overrun accidents. For airports without eligible runway safety areas, safety must be improved using other methods. This study quantifies the overrun risk mitigation effects of different runway safety area improvements, such as purchasing additional land, installing an arrestor system, combining both improvements, and using event tree and consequence analysis. The study then develops a decision-making support process to determine the optimal alternative for improving runway safety areas. Five criteria, namely cost, overrun loss, benefit, benefit over cost ratio, and total expenditure, are used to evaluate the alternatives. The process is then applied to a case study as a demonstration and shows that it can successfully assist decision makers in selecting the optimal alternative. Based on the results, extending the length of a safety area is often the optimum. However, when extending a safety area's length is not feasible, installing arrestor systems following the United States Federal Aviation Administration (FAA) Advice Circular solves the problem.

Key words: *Arrestor system; Event tree; Overrun risk; Runway safety area.*

Introduction

Although the takeoff and landing phases comprise only a small part of a flight, a relatively large number of aviation accidents occur during these two phases. As shown in Fig. 1, the length of takeoff and landing phases only accounted for 1% of an average 1.5-hour-long flight, but 12% and 21% of all fatal accidents occurred during the two phases [1]. Although accidents that occur during on-land movements (takeoff and landing) tend to be less severe than those occurring during the other phases, those accidents actually comprise a significant part of all fatal accidents and can severely impact airport operations [2, 3]. In addition, the runway must be at least partially closed for a certain period after an accident, and the closure will cause schedule delays, and accordingly passengers, airlines, and airport operators will all suffer financial losses because of the accident.

Overrun events include both takeoffs and landings, namely the aircraft cannot complete a takeoff or landing movement within the runway. Once an overrun happens, the overrun aircraft must be stopped within the safety area, i.e., the extended paved area beyond the runway ends. Otherwise, the overrun will likely result in a severe accident. In other words, if the safety area is sufficient in length, the aircraft has higher probability of safely coming to a stop when an overrun occurs.

In order to reduce the risk of aircraft overrun, both the International Civil Aviation Organization (ICAO) and the United States Federal Aviation Administration (FAA) have established detailed regulations about the geometric design of the safety area. In ICAO Annex 14, the paved area set beyond the runway ends includes the Runway Strip and Runway End Safety Area (RESA). The length of runway strip must be 60 m long, and the minimum required length of RESA is 90 m [4]. A recommended length of RESA, 240 m, is also given. Therefore, a runway end must have an extended paved area which is at least 150 m and up to the recommended 300 m in length. On the other hand, according to FAA Advisory Circulars 150/5300-13, besides providing sufficient runway length, airports where the design aircraft has an approaching speed over 121 knots must set a 300-meter-long Runway Safety Area (RSA), the extended paved area beyond the runway end [5]. All federally obligated RSAs must conform to the standard. As seen in these regulations, the required length of RSA stated by FAA and the recommended length of extended paved area stated by ICAO are the same.

Many airports designed their runways and safety areas originally for small aircraft; however, a need for larger aircraft has emerged and the existing safety area is often not long enough to satisfy the length requirements. To solve this problem, FAA provides a set of alternatives for those airports that need to improve their RSAs [6]. In every case, the first alternative that should be considered is the most direct way—obtaining land and expanding the current RSA. All RSA incremental area gains must be obtained whenever possible, even if the gain is relatively small or not rectangular [6]. When the land purchase is impracticable, the airport should enhance the safety by other alternatives, including the following: runway relocation,

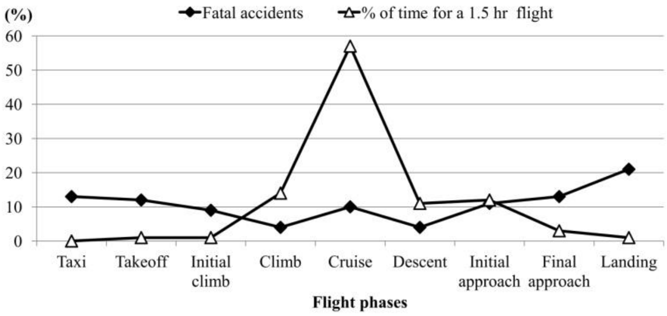

Fig. 1. Percentage of Fatal Accidents during Various Flight Phases.

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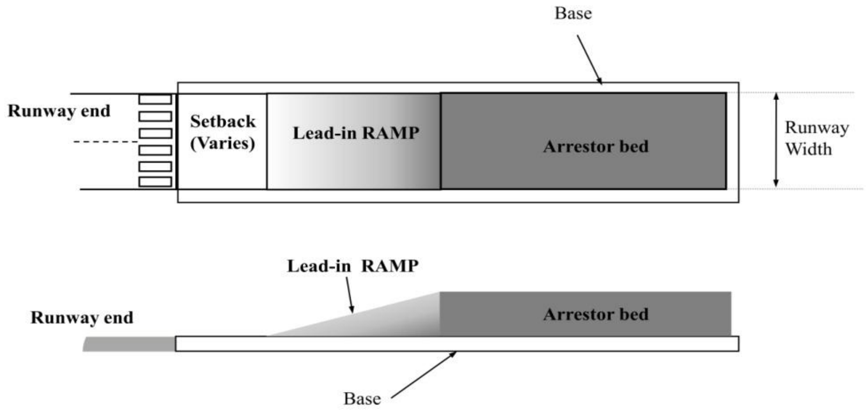

Fig. 2. Typical Plan View of EMAS.

realignment; declared distance; reduction in runway length for the existing or projected design aircraft along with a corresponding expansion of the runway safety area; and arrestor system installation [6].

Since the alternatives that involve changing the geometric design of the runway only address the temporary need, the problem of short RSAs has been solved only in the short term. Among the improvement alternatives, obtaining more land to extend the safety area and installing arrestor systems such as Engineered Materials Arresting System (EMAS) to obtain enough equivalent length are the most effective solutions for airports with high traffic or that are planning to use larger aircraft.

The EMAS is a relatively new runway safety facility produced by the Engineered Arresting Systems Corporation in cooperation with FAA. It is also the only arrestor for commercial aircraft approved by FAA. The ratified EMAS installation can provide an RSA with a length equivalent to the current standard [7, 8]. By 2011, there were 67 sets of EMAS installed in 45 airports, which have shown great successes in arresting overrun aircraft, even large aircraft like Boeing 747. The manufacturer claims that EMAS can stop the overrun aircraft without any gear or passenger damage [9].

The typical plan view of EMAS is shown as Fig. 2. A set of EMAS contains an optional 35-ft-long (about 10.7 m) set-back, a 75-ft-long (about 22.9 m) concrete-paved lead-in ramp, and a length of arrestor bed. Based on the EMAS design guide provided by FAA, the set-back should be set whenever possible to avoid aircraft intrusion during short overruns [8]. The EMAS is a passive system made using a lightweight cementitious material, which is low-strength and can be easily crushed, in order to absorb the moving energy of the overrun aircraft. When the overrun aircraft moves into the arrestor bed, it will crush the cementitious material while decelerating until it comes to a complete stop inside the bed [9].

The geometric design of EMAS varies with the type of design aircraft. The larger the design aircraft, the longer and thicker the EMAS bed should be. Since sometimes there are only few flights using the biggest aircraft, the arrestor system should be designed according to a design aircraft rather than the biggest aircraft to make the improvement economically efficient. If an overrun aircraft is bigger than the design aircraft, the arrestor bed can still lower its overrun damage. However, the probability that the larger aircraft cannot be stopped in the arrestor bed is higher than that of an overrun design aircraft. A standard design of an EMAS must be able to safely stop an aircraft which exits the runway at 70 knots velocity. For the same design aircraft, if the location of the EMAS bed is further away from the runway end, then the length of the EMAS bed can be shortened, and the installation cost of EMAS can be reduced. Therefore, the EMAS bed is often installed as far away as possible from the runway end. Nevertheless, a minimum length that can stop an aircraft leaving the runway end at 40 knots is required by FAA [8].

Just like other airport construction projects, whether the airport improves its safety area by purchasing land, setting EMAS, or combining several alternatives, the cost of the improvement is always high. FAA stated in Order 5200.9 that, in cases where it is impracticable to improve a safety area to meet current standards, it is necessary to consider and address the alternatives and explain the reasons why one is selected over the others [6]. In order to clearly achieve this requirement, it will be helpful to develop a proper alternative analysis method that provides the airport owners and/or operators a tool for determining the most economically sustainable improvement.

Other related FAA documents address the design of safety area improvements and how to evaluate the feasibility of installation and use of EMAS [7, 8]. Those documents do not provide a process to evaluate the efficiency of a safety area improvement but only focus on the cost of RSA improvements rather than the benefit of the alternatives. Since the objective of improving the safety area is not only to make it meet current standards but also mitigate the overrun risk, there is a need for an integrated alternative analysis process that quantifies the risk mitigation of each alternative. To clarify both the benefits and costs of RSA improvements, this study first develops a method to quantify the overrun risk mitigation effects of different improvement strategies, and then establishes five criteria to compare the improvement alternatives (the overrun risk mitigation benefit).

Quantification of Overrun Risk

The difference in accident risk before and after an airport improvement should be considered as a part of benefit [10]. Therefore, the amount of overrun risk mitigation of each

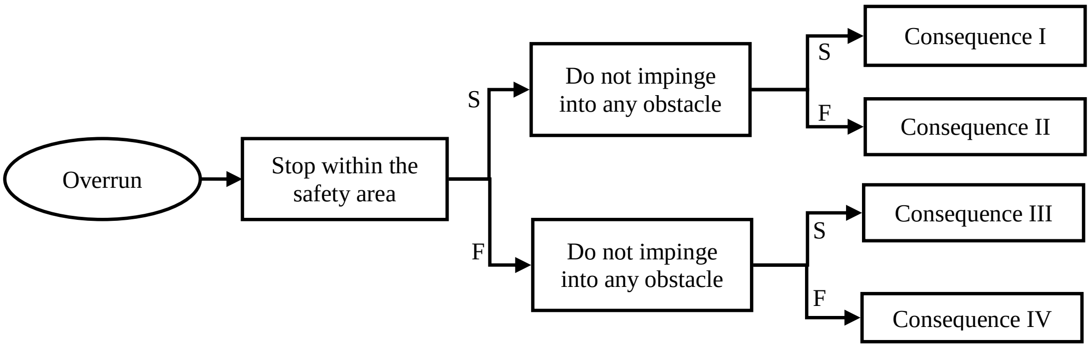

Fig. 3. Event Tree of Overrun without Arrestor Bed.

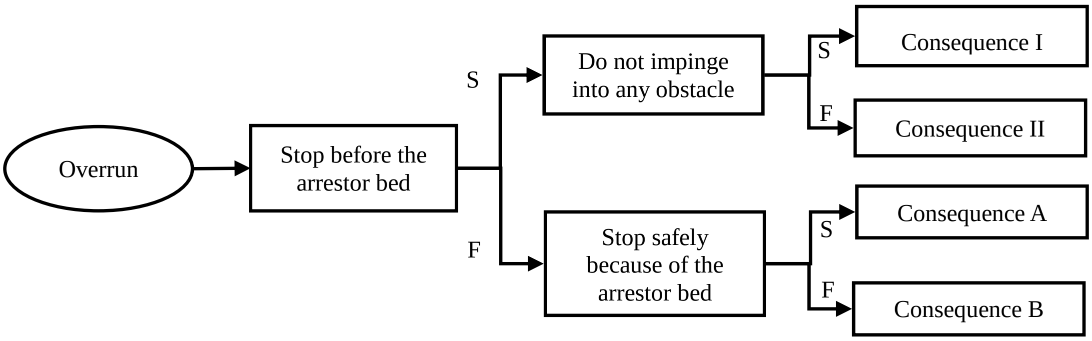

Fig. 4. Event Tree of Overrun with Arrestor Bed Installed.

improvement should be quantified in terms of the monetary unit used to estimate the cost and benefit of the improvement. Because the risk can be assessed by the probability of an event and the severity of its consequence, the approach to mitigating the overrun risk is either to reduce the probability that overruns turn to accidents, or make the accidents less severe [11]. An event tree can be used to describe the sequence of possible events following the hazard and what consequences will result, estimate the probabilities of each problem, and help find solutions to problems [3, 12, 13]. This study uses the event tree and the consequence analysis to present the risk mitigation along the land increase and arrestor system installation, since it is necessary to calculate the probability of each possible consequence after an overrun event to estimate its expected financial loss.

Event Trees of Overrun

If there is no EMAS or similar arrestor system installed, the event tree of an overrun can be presented as Fig. 3. The letters “S” and “F” mean success (S) and failure (F) during the procedures. The probability of each pair of S and F changes under the different background conditions, namely where each runway has its own sets of probability leading to different consequences. The probability of a particular consequence can be estimated by multiplying the probabilities along a path from the hazard to the consequence. For example, when an overrun happens in an airport without EMAS or a similar arrestor system installed, assuming an overrun aircraft has a 10% probability of not stopping within the runway safety area and 30% probability of hitting an obstacle, the probability that the hazard would turn to Consequence IV is 3% and the hazard that would turn to Consequence I is 63%.

On the other hand, if there is an EMAS or similar arrestor system installed, the path from the overrun event to the consequences will follow Fig. 4. If the overrun aircraft does not stop before running into the arrestor bed, it would be either stopped by the arrestor bed safely (Consequence A) or stopped outside the arrestor bed as a severe accident (Consequence B). It is also possible that the aircraft hit an obstacle before running into the arrestor bed. However, in this kind of situation, the damage due to the obstacle is usually minimal, since the aircraft still runs into the arrestor bed.

An overrun event may yield one of the six consequences following different paths as shown in Figs. 3 and 4. The descriptions of each consequence are listed below:

A) Consequence within safety area

- Consequence I: The overrun aircraft comes to a stop within the runway safety area without any collision. The aircraft will have only minor or no damage.
- Consequence II: The overrun aircraft impinges into obstacles within the runway safety area and then comes to a stop. The aircraft and/or some airport facilities may be damaged. Normally, the obstacles appearing in the safety area are foreign object debris, lights, localizer antennas, etc. so this consequence can often be prevented.

B) Consequences out of safety area

- Consequence III：The overrun aircraft comes to a stop out of the safety area, but does not impinge against any obstacle. The aircraft might be damaged, and the severity varies according to the conditions of surrounding terrain.
- Consequence IV：The aircraft cannot stop within the safety area and then impinges against obstacles or stops due to surrounding terrain. The damages to the aircraft and personnel are usually severe.
- Consequence A：The aircraft stops safely because of the installation of an arrestor system, and the aircraft does not run

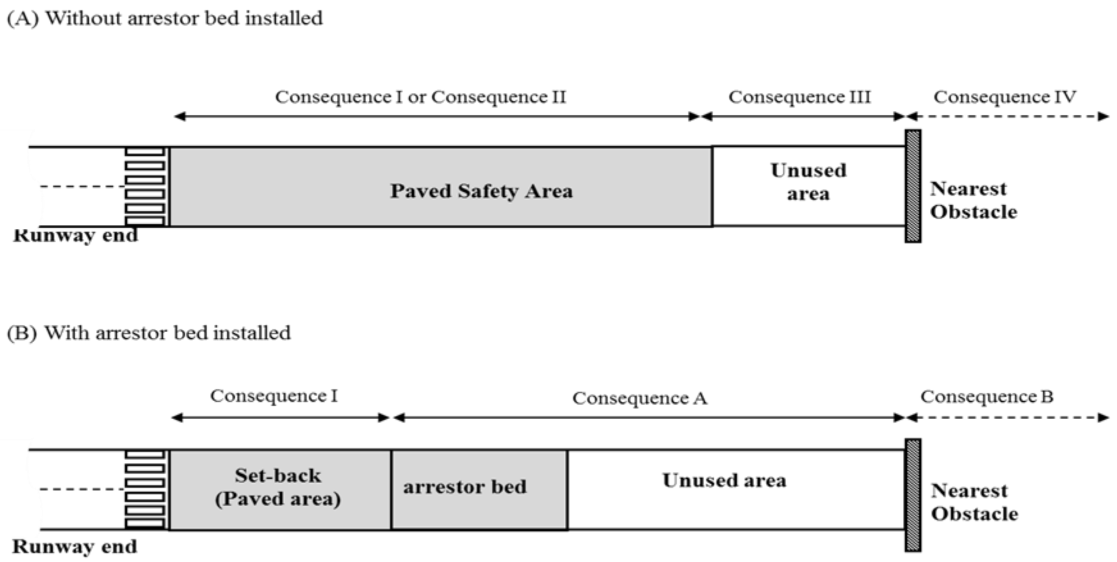

Fig. 5. The Location Where Each Consequence Occurs.

into any obstacles. There will be minor aircraft damage or none at all, but the arrestor bed will need to be repaired.

- Consequence B：The aircraft cannot stop safely, although there is an arrestor system. The aircraft and personnel will be severely damaged, and the arrestor bed will need to be repaired.

Fig. 5 presents the locations where each consequence happens. When there is no arrestor systems installed, the result may be Consequence I, II, III, or IV. On the other hand, when there is an arrestor system installed, the overrun aircraft may experience Consequence I, A, or B.

The degree of damage for each consequence should be evaluated individually. Nevertheless, the consequences can still be simply divided into two categories. The first category includes Consequence I, III and A, and only results in relatively less severe damages to the passengers, crew, and the aircraft because the aircraft eventually stops safely. This category can be defined as less severe consequences. The second category consists of Consequence II, IV, and B. Those consequences cause relatively severe damage to the passengers, crew, and aircraft because the aircraft would impinge upon obstacles. All those consequences are considered as more severe consequences. A successful improvement is able to reduce the probability of more severe consequences and increases that of less severe consequences. Therefore, after improvement, the estimated value of losses should be decreased; this also means the overrun risk is mitigated.

Equivalent Length of Safety Areas with Arrestor Bed

Although the most recommended alternative is increasing land increment [6], environmental concerns or other land usage restrictions often hinder obtaining land. In many cases, airports are not able to improve their safety areas solely by obtaining more land; therefore, both improvement methods, obtaining land and installing an arrestor system, are often implemented at the same time.

As mentioned in the previous section, the size of the arrestor bed needed depends on the type of design aircraft and area available for the runway safety area. Before the installation, the equivalent length of a safety area with an arrestor bed must be calculated to evaluate whether the improved safety area satisfies the current standard. The equivalent length can be calculated using a transform equation shown as Eq. (1).

$$LS = LR + LL + \alpha LB \tag{1}$$

where,
LS is the runway safety area length required in the standard,
LR is the length of the set-back,
LL is the length of the rigid lead-in ramp, and
LB is the length of the arrestor bed,
α is the length equivalent factor of the arrestor bed.

The length equivalent factor, α, indicates the equivalent length of safety area pavement per unit length of arrestor bed. Parameter α is in fact a function of the arrestor bed thickness and may not be a constant; however, it usually is greater than one. Since the thickness varies in a single arrestor bed, α can only be calculated as an average value of each system. Nevertheless, an average value of α is adequate to estimate the efficiency of setting the arrestor bed.

Using the EMAS installation as an example, a preliminary value of bed length can be acquired from the design curves in FAA's AC 150/5220-22A [8]. Since the length and the thickness of an EMAS bed should be decided properly according to the design aircraft, the equivalent factor α is not equal for all types of design aircraft.
Larger and heavier aircraft have smaller α than that of smaller and lighter aircraft, because they need a longer distance to stop. According to FAA statistical data, 90% of overrun aircraft exit the runway with a speed of 70 knots or less [8], and 94% of them would stop within 1,000 ft (about 300 m) of the runway end. Therefore, the EMAS bed is often designed to stop overrun aircraft that exit the runway end with 70 knots speed, and it is reasonable to assume an in-use EMAS bed has the same arresting efficiency as 300-meter-long paved safety area for stopping the design aircraft at 70 knots speed. The ranges of equivalent factor, α, converted from the FAA design curves, are approximately distributed from 1.55 to 3.63.

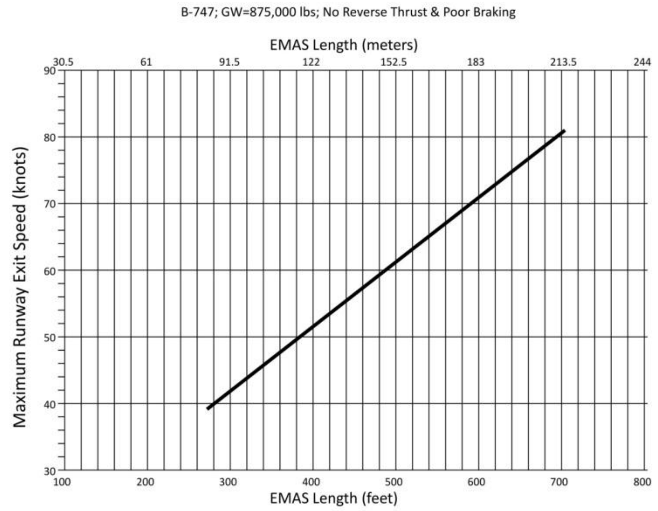

Fig. 6. The EMAS Design Curve of Boeing 747 Provided by FAA [8].

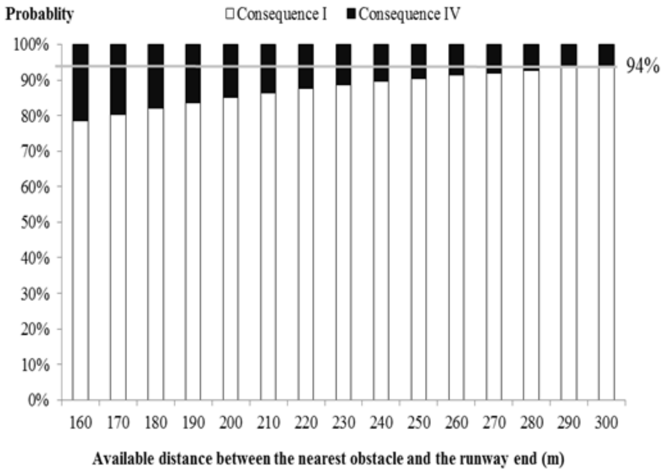

Fig. 7. The Probability of Less Severe Consequences and Severe Consequences under Different Lengths of Useable Land without EMAS.

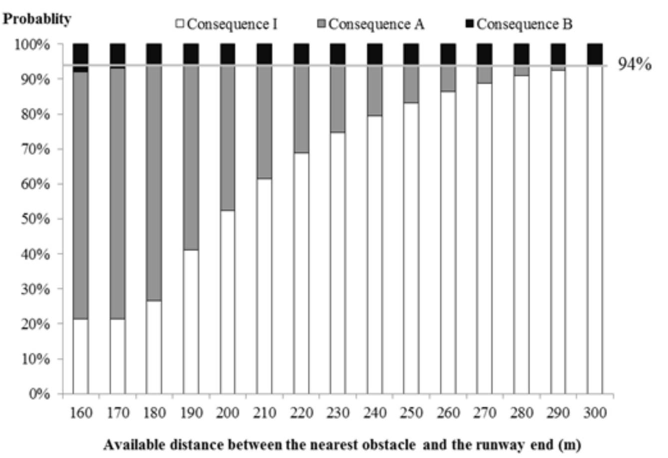

Fig. 8. The Probability of Less Severe Consequences and Severe Consequences under Different Lengths of Useable Land with EMAS.

Based on the FAA design curves (as shown in Fig. 6), a standard EMAS design for a Boeing 747 aircraft is 180 m, including a 10.7 m set-back, a 22.9 m concrete lead-in ramp, and an 146.4 m EMAS bed, when the design exit speed is 70 knots. It is assumed that the EMAS with this configuration has the same safety efficiency as a 300-meter-long paved safety area. Therefore, the equivalent factor for a Boeing 747 at 70 knots exit speed is 1.82, since *LS* is 300 m, *LR* is 10.7 m, *LL* is 22.9 m, and *LB* is 146.4 m.

Estimated Value of Overrun Risk

The expected value of financial loss due to an overrun event, which also represents the amount of risk, can be calculated by Eq. (2). Comparing the disparity of the expected values of financial loss before and after an improvement, the benefit of the improvement to risk mitigation can be quantitatively presented.

$$l = \sum l_j \times P_j \tag{2}$$

where,
l is the estimated value of loss due to an overrun event,
l_j is the loss of the jth consequence, and
P_j is the probability of the jth consequence realization.

To obtain the P_j in Eq. (2), an aircraft stopping location model is needed. Hall (2008) analyzed overrun and undershoots accident records from several aviation databases, and then built three models to assess the risk of in-airport aviation accidents [2]. Eq. (3) is a Location Model, which can be used to predict the probability that an overrun aircraft will stop at a specific distance from the runway end. In Eq. (3), P is the probability that the overrun distance, d, is greater than x, and x is the distance from the runway end (m). The model was developed based on 257 overrun accidents, with a high coefficient of determination ($R^2 = 0.998$).

$$P\{d > x\} = exp^{-0.003871\,(x/0.31)^{0.955175}} \tag{3}$$

This study calculated the probability of each consequence by applying Eq. (3) as presented in Figs. 7 and 8. (Fig. 7 is the result when there is no arrestor system, and Fig. 8 is the result with arrestor system.) With varied x, available distance between the runway end and the nearest obstacle like fences, roads, or rivers, the probabilities of each consequence change. Assuming there are no obstacles occurring in the safety area and the safety area has already been extended to the longest length possible, the probabilities of Consequence II and Consequence III are 0. The longer the distance between the runway end and the nearest obstacle is, the higher the probability of Consequence I (the less severe consequence), and the lower the probability of Consequence IV (the more severe consequence). Data shown in Fig. 7 are also consistent with the FAA statistics, that is, about 94% of overrun aircraft can stop within 300 m from the runway end [14].

Fig. 8 presents the cases with arrestor system installed for the Boeing 747's specifications. It is reasonable to assume that there are no obstacles on the set-back, and the arrestor bed should be installed at the furthest location away from the runway end. Once the standard EMAS design of Boeing 747 needs is installed, namely

180 m, the probability of Consequence B (the severe one) keeps constant at 6%. It is obvious that when the available distance between the runway end and the nearest obstacle is less than 300 m, with EMAS, the probability of a more severe consequence is reduced to the same probability as for a 300-meter paved area.

There are two less severe consequences, Consequence I and Consequence A, when there is an arrestor system installed. As shown in Fig. 8, the length of the EMAS bed decreases with an equivalent factor of 1.82 while the length of available land increases, so the probability of Consequence A decreases and that of Consequence I increases. When the available land is 300 m, there is no need to set up an arrestor system, so the probability of Consequence A is 0.

Although the installation of an arrestor system leads to a low probability of more severe consequences, it does not necessarily secure lower expected value of financial loss. In fact, the loss associated with Consequence A might be large, because the airport authorities or airlines would need to pay the repair fees for the arrestor bed even if there is no damage to passengers or aircraft. The EMAS improvement may bring benefits of reducing the damages but also increases the repair cost at the same time. Therefore, it is important to conduct an analysis to understand both cost and benefit of each improvement.

Evaluation of Runway Safety Area Improvements

To compare the differences among the alternatives, the cost and benefit of each alternative must be quantified by numerical values. The Cost-Benefit Analysis (CBA) is a very common method to evaluate alternatives in terms of a monetary unit. Because there are cases where not all factors can be evaluated as quantifiable values, like environmental or safety impact, it is necessary to transform those factors into a monetary unit or other indices [15, 16]. In the case of safety area improvement analysis, the CBA method is adopted to evaluate the alternatives. Five criteria, namely the initial inventory cost, the overrun loss, the disparity of the loss values before and after an improvement, the benefit over cost ratio, and the total expenditure, are established in this study to evaluate the performance of the alternatives of runway safety area improvement. The detailed description of each criterion is presented as below.

The Initial Investment Cost

If the safety area is improved by obtaining more land, the costs include the price paid for the extra land and construction. On the other hand, if the runway safety area is improved with an arrestor system, the costs include the expenditure of the materials, installation, and regular maintenance during its service life. For the case that both alternatives are selected, the cost shall include all items, as listed in Eq. (4).

$$Ci = CL + CA + CI \tag{4}$$

In Eq. (4), Ci is the total cost of alternative i, which is the summation of the possible costs of all items needed in the improvement, CL is the cost of buying land and safety area construction, CA is the cost of the arrestor bed material, and CI is the cost of the arrestor system installation and regular maintenance.

The cost is the investment needed to improve the safety area right at the beginning. Some airports that do not have a large capital budget might consider the cost as a very important criterion. The longer the original safety area is, the lower the cost of improving the runway safety area, no matter which improvement is applied. Land price varies greatly across different regions. Since the equivalent length of the arrestor bed can be calculated through the analysis, it is not difficult to determine whether the land price is too high. Obtaining extra land for extending a safety area is considered practical as long as the price of setting up a runway safety area per unit area does not exceed the price of arrestor bed per unit area times the design’s equivalent factor. This is also the reason why when there is a need to improve the RSA, FAA always suggests that the airport should extend the ineligible RSA with any possible land increment before other alternatives. The worst situation is when it is not practical to obtain more land, and the available inventory also cannot allow installation of a long-enough arrestor bed. In this case, the airport can only modify its runways, limit the usage of large aircraft, or reduce the length of runway to provide enough length of safety area.

The Overrun Loss

The definition of overrun loss here is the monetary expression of the loss due to the overrun event during the analysis period. Once an overrun has occurred, all losses of the airport, airlines, and passengers due to direct damages, runway closures, and schedule delays are encountered. Additionally, costs associated with some facilities and the repair fees of the arrestor bed shall be also included.

The overrun loss can be calculated by Eq. (5), where Li is the total loss due to overrun with alternative i, Q is the expected number of overrun occurrences during the analysis period, and li is the expected loss of an overrun with alternative i. The expected value of loss of an overrun event is the combination of the event’s probability and severity.

$$L_i = Q \times l_i \tag{5}$$

$$l_i = \Sigma P_{ij} \times (lA_{ij} + lD_{ij} + lE_{ij}) \tag{6}$$

where,
l_i is the summation of the loss of each consequence, which can be expressed as Eq. (6),
P_{ij} is the probability of Consequence j with alternative i,
lA_{ij} is the loss due to the fatalities and injured passengers or crews and aircraft damage,
lD_{ij} is the losses of passengers, airlines and airport due to runway closure and schedule delays, and
lE_{ij} is the cost for arrestor bed repair after the event. lE_{ij} is 0 if no arrestor system is installed.

As shown in Figs. 7 and 8, the probability of Consequence I decreases when there is an arrestor system installed. Since repair of the arrestor bed is usually expensive, the loss associated with Consequence A may be relatively higher than that of Consequence I, and consequently the expected value of the loss with an arrestor system may be higher than the one without an arrestor system. If the arrestor bed is installed too close to the runway end, the probability that an overrun aircraft runs into the arrestor bed will increase and lead to a higher repair cost. Besides, the longer the distance in front of the arrestor bed, the shorter the needed arrestor bed, thus reducing the cost of installation.

The Disparity of Loss Values before and after an Improvement

The benefit of an alternative *i*, B_i, can be calculated by Eq. (7). L_0 is the accident loss without any improvement, and L_i is the accident loss with alternative *i*. So B_i is the difference of loss value before and after the implementation of improvement alternative *i*.

$$B_i = L_0 - L_i \tag{7}$$

The Benefit over Cost Ratio

After B_i and C_i are calculated from Eqs. (4) and (7), the *B*/*C* ratio of alternative *i*, R_i, can be obtained by Eq. (8). It represents the financial efficiency of an alternative.

$$R_i = B_i / C_i \tag{8}$$

The Total Expenditure

The total expenditure of an improvement is the sum of all the costs and accident losses over the analysis period, which can be presented as Eq. (9). TE_i means the total expenditure of applying alternative *i*.

$$TE_i = C_i + L_i \tag{9}$$

The *B*/*C* ratio and total expenditure consider the alternatives featured on both the financial and safety sides. A larger *B*/*C* ratio means the alternative has either better efficiency (greater benefit) or lower cost. Since the cost of runway safety area improvement is often huge and only a partial benefit can be represented in monetary terms, the value of *B*/*C* ratio usually is smaller than 1. Despite that, the investment of RSA improvement is still necessary in order to meet the standard in length.

Obtaining land to extend the safety area or installing arrestor systems can be an optional improvement for an airport. The decision could be made from financial or safety considerations. When the decision maker pays more attention to the financial aspect, the objective may be to minimize the cost. Whenever the decision maker determines that safety is more important, the objective may be to minimize the overrun loss and to maximize the benefit. If the decision maker wants to make the decision in a more comprehensive way, then the objective may be to maximize the *B*/*C* ratio or minimize the total expenditure. The baseline of all the alternatives is “do nothing” which has no additional cost at all. Thus, the total expenditure of any improvement is always larger than “do nothing.” However, once the improvement becomes necessary, “do nothing” cannot be one of the options.

Case Study

The evaluation process is applied to a case study of an airport as a demonstration. As shown in Fig. 9, the safety area of this airport is only 90 m and needs to be improved significantly. Since the safety area cannot be extended to 300 m except through the purchase of additional land, three alternatives are considered to make the safety area satisfy the requirement of 300 m equivalent length with arrestor system installation. The only type of arrestor system approved by FAA, EMAS, is selected in this case. The design aircraft of the airport is given as Boeing 747 (with an equivalent factor α =1.82), and the other information needed to evaluate the three alternatives are listed in Table 1. In this table, an estimated unit price of EMAS is given based on the local airport experience; however, it may vary due to different conditions.

Table 2 lists the current situation (do nothing) and the alternatives and also the equivalent length of EMAS and the entire safety area respectively. The difference among the three alternatives is the location of the EMAS bed. Alternative EMAS1 sets the EMAS bed right next to the runway end. The length of entire EMAS system needed is 180 m, including a 10.7 m set-back pavement, a 22.9 m lead-in ramp and a 146.4 m arrestor bed. On the other hand, the alternative EMAS2 and EMAS3 set the arrestor bed further away from the runway end. Alternative EMAS 2 set the arrestor bed at the farthest location from the runway end with the minimum length of the bed. The required length of the arrestor bed is reduced with the increased length of pavement in front of the arrestor bed; however,

Fig. 9. Current Situation of the Airport for Case Study.

Table 1. Information Needed for Evaluation of Airport A.

Operation Information	
Passenger Volume	3,101,854 (Passenger/Year)
Average Takeoff and Landing Flights Per Hour	5.6 (Flight/hr)
Average Income Per Takeoff or Landing	294.12 (USD)
Cost Information	
Land Price	1,470.59 (USD /m²)
Construction Fee of Safety Area Pavement	205.88 (USD /m²)
Unit Price of EMAS (Including Material Installation and Regular Maintenance)	1081.88 (USD/m²)[a]
Width of Safety Area and EMAS Bed	70 (m)
Repair Cost of EMAS	25% of its Initial Cost

[a] assuming the thickness of EMAS bed is properly designed by the agent

Table 2. Equivalent Length of Alternatives for Airport A (Unit: m).

Length of Each Item \ Alternatives		Do Nothing	EMAS1	EMAS2	EMAS3
Set-back	L_R	90	10.7	162.1	122.4
Lead-in Ramp	L_L	0	22.9	22.9	22.9
Paved Area (Between the Runway End and the Arrestor Bed)	$L_R + L_L$	90	33.6	185	145.3
EMAS Bed	L_B	0	146.4	85	85
Land Needed to Set the Entire System	$L_R + L_L + L_B$	90	180	270	230.3
Extra Land Needed		0	90	180	140.3
Equivalent Length of Safety Area	L_S	90	300.05	339.7	300
Equivalent Length from Runway End to Nearest Obstacle	X	270	390.05	339.7	339.7

Table 3. The Expected Values of Loss of Each Consequence Per Event.

Consequence	j	l_j (USD Per Event)
I	1	12,568.76
II	2	1,158,042.56
III	3	3,846,164.77
IV	4	6,150,862.94
A	5	The Loss of Consequence I + EMAS Repair*
B	6	The Loss of Consequence IV + EMAS Repair*

*The losses of consequence A and consequence B vary according to type of EMAS design.

FAA suggests that the minimum length of the EMAS bed should be able to arrest the design aircraft at 40 knots exit speed.

From the FAA design curves, the minimum length of the EMAS bed from the Boeing 747 is 280 feet (about 85 m) long [8]. Therefore, in Alternative EMAS2, besides the current 90-meter-long safety area, the airport needs to buy extra 180 m of land to accommodate the entire 270 m system. The distance between the arrestor bed and the runway end is 185 m, and the equivalent length from the runway end to the nearest obstacle will be 339.7 m, according to Eq. (1).

Alternative EMAS3 also sets the EMAS bed with the minimum length. However, it sets the EMAS bed just at the location where it provides a 300-meter-long equivalent length of safety area. Accordingly, the distance between the runway end and the arrestor bed is 145.3 m, and the equivalent total length of the safety area is exactly 300 m. With this alternative, the airport only needs to buy 140.3 m of land for the entire system. In addition, because there is still a 39.7 m strip of land, which does not belong to the airport, between the end of arrestor bed and the nearest obstacle, the equivalent length from the runway end to the nearest obstacle is 339.7 m.

Table 3 shows the amount of losses of each consequence (l_j) per event in Airport A. The information here is estimated from historical accident data of National Transportation Safety Board, US and Aviation Safety Council, Taiwan. It is obvious that the losses associated with Consequence III and Consequence IV are much higher than those with Consequence I and Consequence II. Among them, the loss of Consequence B is the highest out of the six consequences. The probabilities of the consequences when taking different alternatives (P_{ij}) can be obtained by applying the equivalent lengths in Table 2 as the x into Eq. (3). The calculated results are shown in Table 4.

Through Eq. (4) to Eq. (9), the values of the five criteria are calculated and shown in Table 5. It is found that all B/C ratios are much smaller than 1.0, and alternative EMAS1 even has a negative B/C ratio. This is due to the huge investment of installing EMAS compared to the relatively low benefit from reducing losses. However, meeting the safety standard is extremely important, so it is suggested that the B/C ratio is used as a reference for decision making. From Table 5, alternative EMAS2 shows the best performance. It has not only the largest reduction of losses, but has the greatest benefit and B/C ratio as well as the lowest total

Table 4. Probabilities of the Consequences when Taking Different Alternatives (P_{ij}).

Alternative \ Consequence	I	II[a]	III[b]	IV[b]	A[c]	B[c]
Do Nothing	58.75%	0.00%	33.27%	7.97%		
EMAS1	29.22%	0.00%			68.04%	2.75%
EMAS2	82.84%	0.00%			12.88%	4.29%
EMAS3	75.32%	0.00%			20.39%	4.29%

[a] Assuming there are no obstacles within the runway safety area or the set-back.
[b] Only doing nothing may end with Consequence III or Consequence IV.
[c] Only the alternatives with arrestor bed installed may end with Consequence A or Consequence B.

Table 5. Evaluation Results of Each Alternative (Unit: USD).

Alternatives	Cost	Loss	Benefit	Total Expenditure	B/C Ratio
Do nothing	0.00	430,186.82	0.00	430,186.82	-
EMAS1	11,238,012.71	1,970,193.32	-1,540,006.50	13,208,206.03	-0.1370
EMAS2	6,738,964.71	297,452.09	132,734.74	7,036,416.79	0.0197
EMAS3	6,672,408.82	417,476.97	12,709.85	7,089,885.79	0.0019

expenditure. Although the initial cost of alternative EMAS2 is slightly higher than that of alternative EMAS3, the benefit of EMAS2 is much higher. This is because in alternative EMAS2, the arrestor bed is further from the runway end, leading to a lower probability of more severe consequences and necessary repair of the arrestor bed. Alternative EMAS1 sets the arrestor bed closer to the runway end. As a result, it has relatively high probability of Consequence A, which requires a much higher repair fee for the arrestor bed. Therefore, alternative EMAS1 has a negative benefit and its expected value of loss per event is much higher than those of the other alternatives. In addition, “do nothing” will not be an option since it does not improve the current condition at all; therefore, the airport does not meet the safety requirement.

Conclusions

This study develops a process to quantify the overrun risk before and after an improvement to a runway safety area. Event trees are established for describing the sequence from the overrun event to the consequence. Then, the expected value of losses of an overrun event is calculated associated with the equivalent length of each segment of the safety area. According to the consequence analysis in this study, setting up an arrestor bed can indeed reduce the possibility that the overrun event leads to more severe consequences and makes the safety efficiency equal to that of an eligible runway safety area.

Since the cost of safety improvement is high, a procedure of alternative analysis is developed in this study to integrate the financial and safety concerns of the alternatives and help decision makers choose the optimal improvement. Five criteria—cost, overrun loss, benefit, B/C ratio, and total expenditure—are presented to evaluate the alternatives. According to the case study presented in this paper, the developed evaluation process can successfully estimate the amount of risk mitigation measures. The best alternative out of four could be selected based on the five established criteria.

The performance of each alternative cannot be calculated accurately without correct and detailed information. The information and historical loss record of each airport should be gathered and analyzed based on its own unique conditions to estimate the extent of risk that could be reduced by implementing a runway safety area improvement. Since safety is paramount, any improvement that can reduce losses, especially fatal losses, is considered a feasible alternative even if the financial efficiency seems minor. This study provides a tool for airport authorities to understand more about the overrun risk and to select the most appropriate improvement alternative based on the analysis results.

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