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A Fuzzy-based Site Selection Framework for Emergency Landings of Commercial Aircraft

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It is rare for a commercial passenger aircraft to be forced to carry out an emergency landing. Nevertheless, when such an event occurs, pilots are responsible for selecting a suitable landing site and flying the aircraft towards that site for a safe landing. This study addresses the challenges associated with the selection of the best emergency landing site – in a total loss of thrust scenario – by proposing a fuzzy logic framework which mimics the reasoning and decision-making process of airline pilots. The framework consists of a number of fuzzy logic systems which are used to quantify the risk associated with each landing site (conventional or unconventional) within the remaining gliding distance of the aircraft. The landing sites are then ranked in order of risk and presented to the crew. This risk assessment is not limited to the landing sites themselves, but also accounts for risks associated with the trajectories leading to those sites. Various aspects of the fuzzy logic framework – including the fuzzy variables, fuzzy sets, membership functions and fuzzy rules – were defined with the input of experienced commercial airline pilots and are discussed in this paper. The results of a preliminary evaluation of the proposed framework demonstrate its suitability for the intended scenario.

I. Introduction

There are various situations during a commercial flight where the crew may be required to deviate from their flight plan. This is especially true during the descent and approach parts of the flight where unforeseen Air Traffic Control (ATC) constraints may affect both the lateral and vertical profiles being flown. Such constraints may occur, for example, when descent clearances are delayed or level segments are introduced or extended. There are other reasons beyond ATC constraints that may require alterations to the flight path, including weather avoidance or aircraft energy management. In each case, the adjustment of the descent profile, especially when both the vertical and lateral profiles need to be changed, leads to an increase in crew workload. This is more significant during non-nominal or emergency situations in which the crew are required to conduct an assessment of the aircraft's performance capability, possibly identify an alternative landing site, and then update the flight profile in order to bring the aircraft's energy in line with the desired levels for landing.

Various situations can force the crew of a commercial passenger aircraft to perform an emergency landing, including: Total Loss of Thrust (TLOT), onboard fire, structural damage and hydraulic failure. The onboard automation of current passenger aircraft – such as the A320 and B737 – provides limited assistance in these situations. For instance, the Flight Management System (FMS) provides a list of nearby airports; however, it is up to the crew to identify the most suitable landing site and to fly towards it whilst avoiding hazardous weather, high terrain, and other

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obstacles along the way. The chances of a successful landing depend on various factors, including the ability of the crew to: react quickly and assess the post-failure performance of the aircraft; evaluate different landing options and make tradeoffs between various criteria; and fly the aircraft in a way that it can reach the selected landing site at a safe height and speed. The literature review shows that emergency situations can happen in various phases of flight. Table 1 summarizes a selection of emergency landings due to TLOT.

The rest of this manuscript is organized as follows. Section II provides a literature review and introduces the proposed approach. Section III presents the fuzzy logic framework, including the fuzzy logic systems, fuzzy input variables and fuzzy sets, and fuzzy rules. Section IV presents preliminary test results and, finally, Section V summarizes the paper and discusses future work.

Table 1. A selection of TLOT accidents which occurred between 1980 and 2020

Ref.	**Year**	**Aircraft type**	**Cause of loss of thrust**	**Phase of flight**	**Landing site**
[1]	1988	Boeing 737-3T0	Dual engine flameout due to water ingestion	En route	Unconventional (grass strip)
[2]	1993	Airbus A300B2-101	Fuel starvation	Landing	Unconventional (open paddy field)
[3]	2000	Airbus A310-304	Fuel starvation	Landing	Unconventional (grass)
[4]	2000	Boeing 707-312B	Inflight fire (short circuit)	Landing	Conventional
[5]	2008	Boeing 727-259	Fuel starvation	Approach	Unconventional (Amazon jungle clearing)
[6]-[8]	2009	Airbus A320-214	Dual engine failure due to bird strike	Initial climb	Unconventional (ditching on the Hudson river)
[9]	2009	Boeing 707-3J9C	Uncontained engine failure	En route	Conventional
[10]	2010	Tupolev Tu-154M	Electrical system problem	En route	Conventional
[11]	2019	Airbus A321-211	Dual engine failure due to bird strike	Initial climb	Unconventional (corn field)
[12]	2019	Sukhoi Superjet 100	Electrical system failure	Climb	Conventional

II. Literature Review and Proposed Approach

The process leading to the selection of a landing site has to account for the influence of various factors, including: the glide performance of the aircraft; the aircraft's altitude at the onset of the emergency situation; the prevailing weather conditions; the distance to each candidate landing site; and the physical characteristics of each landing site. Assuming that information on these factors is available and quantifiable, a computerised system that can quickly evaluate and rank potential landing sites – on the basis of risk – would be very useful and is highly desirable.

A number of studies have been carried out on emergency landing site selection, with applications ranging from general aviation and commercial air transport, to manned fighter aircraft and Unmanned Aerial Vehicles (UAVs). In the majority of cases, conventional landing sites (i.e. airfields) are selected and ranked on the basis of the characteristics of the landing sites themselves, without consideration for the complete emergency trajectory. For example, in [13],[14], a utility function is defined to assess landing sites on the basis of airport and weather information e.g. runway length, instrument approach quality, crosswind, etc. A similar approach is used in [15] to rank different landing sites within gliding distance of the aircraft. In contrast, Meuleau et al. [16] assess the risk of candidate landing sites by identifying the risks associated with each segment of the emergency landing, namely: en route, approach, landing and airport. Similarly, in [17], a number of safety metrics are defined to rank different trajectories to the same runway e.g. number of turns, total length, average distance from runway, etc.

This work proposes a slightly different approach to landing site selection and evaluation. Firstly, the proposed approach can be used to identify and assess both conventional and unconventional landing sites. This is particularly advantageous in situations where no conventional landing sites are within reach. Secondly, the risk associated with each potential landing site is calculated by taking into account the risks which are specific to the landing site itself (such as the runway length), as well as the risks which are related to the entire landing trajectory (such as hazardous weather, high terrain and densely populated areas). This results in a more comprehensive risk assessment of each candidate landing site.

This paper proposes a fuzzy logic approach to the risk assessment of potential landing sites. The overall process for landing site identification and risk assessment is shown in Figure 1. Steps 1-3 are first carried out to provide inputs to the fuzzy logic framework in Step 4. The details of these preparatory functions (i.e. Steps 1-3) are beyond the scope of this paper and will be assumed available and accurate. The rest of this paper will therefore focus on Step 4 (i.e. the fuzzy logic framework).

The authors are aware that replicating the thought process of the flight crew is not a trivial task and that there are factors, such as crew experience and intuition, that cannot be quantified and taken into account by the proposed framework. For example, pilot familiarity with a particular landing site cannot be factored into the framework. Furthermore, the authors feel that conventional and unconventional landing sites cannot be assessed using the exact same group of risk factors and that, given a choice between a conventional landing site and an unconventional landing site, pilots will invariably favor the conventional landing site. For this reason, the proposed framework will assess conventional and unconventional sites separately and present them to the crew (in Step 5) as two separate lists.

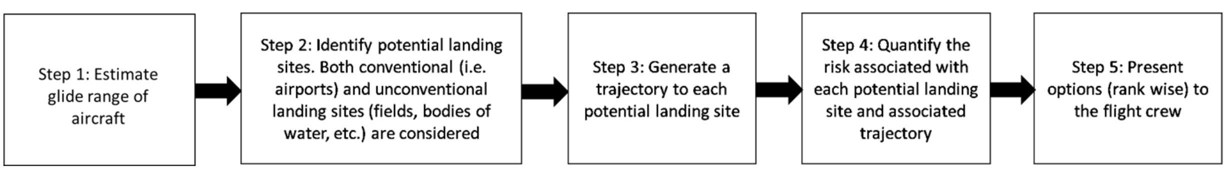

Fig. 1 Block diagram of the overall process.

III. Fuzzy Logic Framework

A fuzzy logic framework is proposed in this work for a number of reasons: (a) it allows rules to be defined by, and be understandable to, human experts, thus making it easier to incorporate the knowledge of end-users (i.e. pilots); (b) it is able to handle uncertainties and noise in the input variables; and (c) the problem of emergency landing site selection is based on approximate reasoning. The rest of this section discusses the details of the fuzzy logic framework.

A. Fuzzy Logic Systems

Rather than consisting of one large fuzzy logic system – which would be very hard to manage and understand – the proposed framework consists of multiple fuzzy logic sub-systems, each corresponding to a particular phase of an emergency landing (descent, approach and landing) and to general risk factors (which are not associated with any specific phase of flight). The outputs of these sub-systems are risk scores which are combined into a final risk value using the cascaded fuzzy logic approach shown in Figure 2. This is similar to the approach taken in [18], where multiple fuzzy reasoning phases are used to select a landing site during autonomous spacecraft descent. As can be observed from Figure 2, the Landing block of the framework consists of three fuzzy logic sub-systems: one to process risk factors that are specific to conventional sites; one to process risk factors which are specific to unconventional sites; and another to process risk factors which are common to all sites.

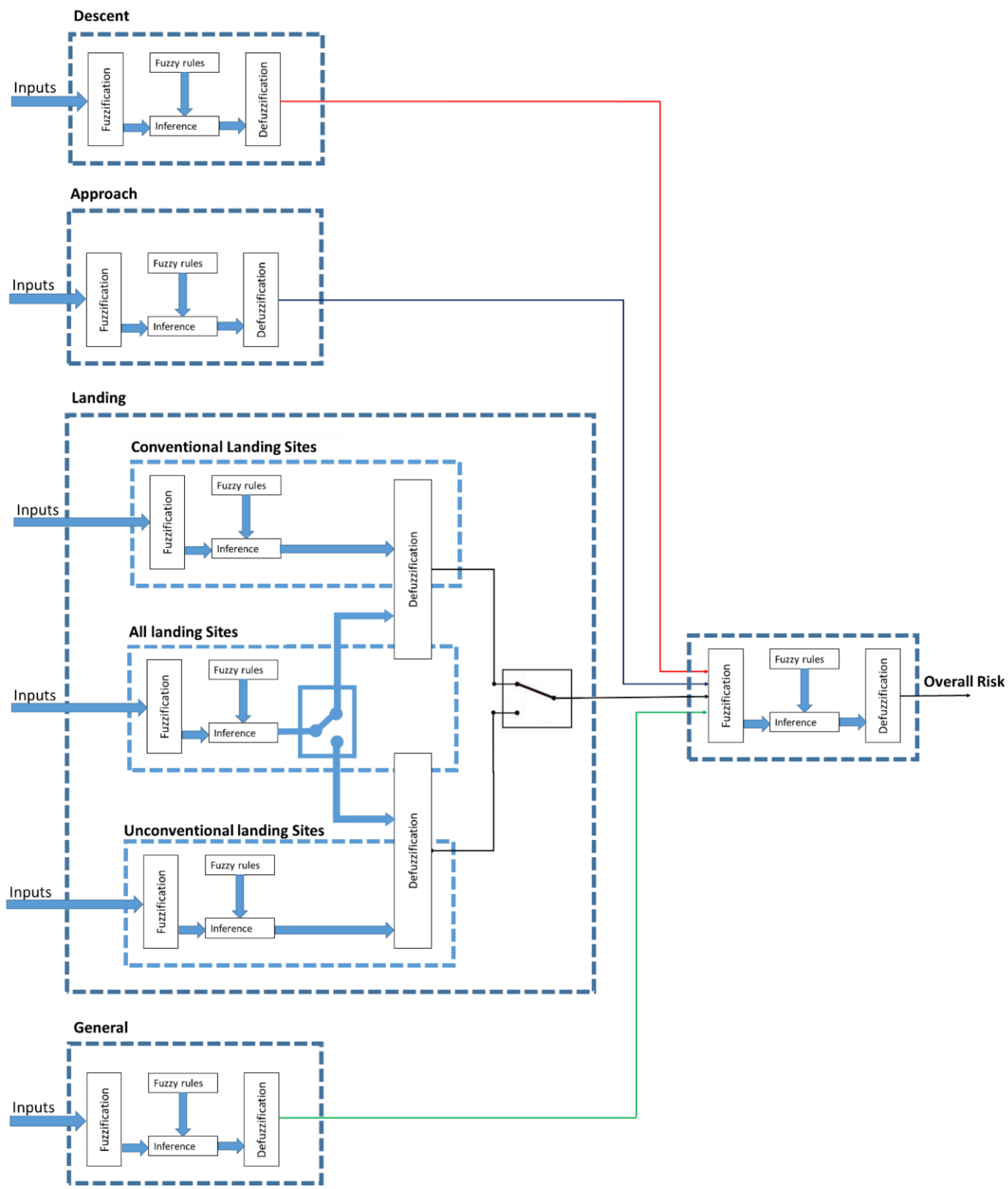

Fig. 2 Top-level block diagram of the fuzzy logic framework consisting of multiple fuzzy logic sub-systems.

The proposed framework is expected to provide a number of advantages over other emergency landing site selection approaches, namely: the ability to design fuzzy rules that are dedicated to a particular segment of the flight; the possibility of adjusting the membership functions of common inputs in different flight segments; the possibility of assessing the risk of both conventional and unconventional landing sites by enabling or disabling fuzzy logic sub-systems as required during execution; and, finally, the ability to tune the fuzzy logic sub-system that computes the overall risk. From a user perspective, this approach is more user-friendly as it provides a clear segregation of the risk assessment associated with each segment. This is important given the large number of rules that need to be defined and possibly adjusted during the operational lifetime of the framework.

B. Fuzzy Input Variables and Fuzzy Sets

The input variables of each fuzzy logic sub-system, together with their fuzzy sets and boundaries, are defined in Table 2. Where applicable, boundary values are based on the Airbus A320.

For the Descent segment, the fuzzy input variables correspond to thunderstorm and terrain clearance. Below 5,000 feet Above Ground Level (AGL), the aircraft enters the Approach segment and additional fuzzy input variables – related to weather and population density – are introduced. The variable 'Population density' takes into account the risk associated with flying over populated regions (e.g. cities).

The fuzzy input variables for the Landing segment are divided into three categories: variables which are specific to conventional landing sites; variables which are specific to unconventional landing sites (not presented in this paper); and variables which are applicable to all landing sites. Most of these variables are self-explanatory. The variable 'Airport facilities' accounts for four main types of facilities: emergency, approach and runway lighting, maintenance, and fuel facilities. This variable is assigned a score between 0 and 100, where a score of '100' corresponds to an airport equipped with all the facilities required for an A320. Of these, the emergency and lighting facilities are considered to be the most critical factors. The variable 'Instrument approach' is also assigned a score between 0 and 100 and has three fuzzy sets associated with it. For instance, a POOR score could be assigned to a landing site which only has an NDB/VOR approach; an ADEQUATE score could be assigned to a landing site which only has a GNSS/RNAV approach; and a GOOD score could be assigned to a landing site with an ILS approach. The variable 'Horizontal distance to landing site' is expressed as a fraction of the glide distance and can take a value between 0 and 1, where '0' implies that the landing site is directly below the aircraft and '1' indicates that the landing site is at the edge of the glide footprint of the aircraft.

The General group of fuzzy input variables corresponds to risk factors which are independent of the phase of flight, such as aircraft weight. The variable 'Heading change' is the heading change required to align the aircraft with a particular landing site, and is used as a proxy for the complexity of the emergency landing trajectory. Note that traffic is not included as a risk factor. This is because it is assumed that, in the event of an emergency landing, ATC would divert any traffic away from the damaged aircraft.

A mix of triangular and trapezoidal shapes were selected for the membership functions of the fuzzy input variables. As an example, Figure 3 shows the membership functions corresponding to the fuzzy sets of the variable 'Horizontal thunderstorm clearance (upwind)'.

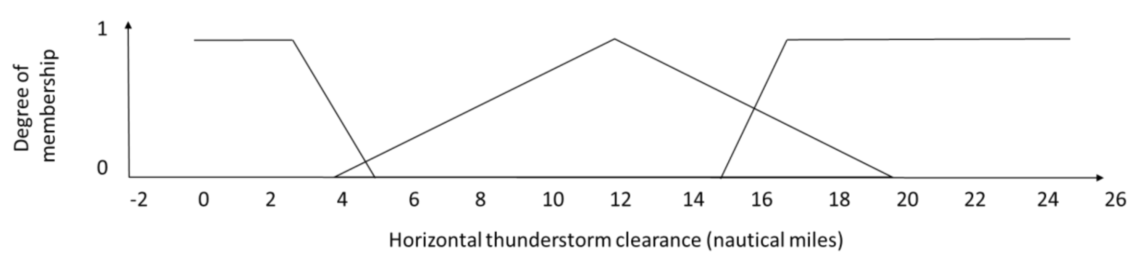

Fig. 3 Membership functions corresponding to the fuzzy sets of 'Horizontal thunderstorm clearance'.

Table 2. Fuzzy input variables for emergency landings due to TLOT

Emergency flight segment		Input variables (aka linguistic variables)	Units	Fuzzy sets	Boundaries
Descent		Vertical terrain/obstacle clearance	feet	LOW MEDIUM HIGH	< 1800 1700 to 2300 > 2200
		Horizontal thunderstorm clearance (upwind)	nautical miles	LOW MEDIUM HIGH	< 5 4 to 20 > 15
Approach		Vertical terrain/obstacle clearance	feet	LOW MEDIUM HIGH	< 1300 1200 to 1800 > 1700
		Horizontal thunderstorm clearance (upwind)	nautical miles	LOW MEDIUM HIGH	< 5 4 to 20 > 15
		Population density	number of people per km^2	LOW MEDIUM HIGH	< 15,000 10,000 to 30,000 > 25,000
		Visibility	meters	LOW MEDIUM HIGH	< 1,000 800 to 5,500 > 5,000
		Cloud cover	oktas	LOW MEDIUM HIGH	1 to 4 3 to 7 6 to 8
Landing	Conventional landing sites (airports)[4]	Runway length	meters	SHORT AVERAGE LONG	< 1800 1600 to 2000 > 1900
		Runway width	meters	NARROW AVERAGE WIDE	< 40 30 to 55 > 45
		Runway surface friction (Runway Condition Code)	-	GOOD MEDIUM POOR	4 to 6 2 to 4.5 0 to 2.5
		Airport facilities	-	POOR ADEQUATE GOOD	< 40 30 to 75 > 70
		Instrument approach	-	POOR ADEQUATE GOOD	< 40 30 to 75 > 70
		Visibility	meters	LOW MEDIUM HIGH	< 1,000 800 to 5,500 > 5,000
	All landing sites	Horizontal distance to landing site	-	VERY CLOSE NEAR FAR	0 to 0.4 0.3 to 0.7 0.6 to 1
		Headwind/tailwind	knots	STRONG TAILWIND MODERATE TAILWIND LIGHT WIND MODERATE HEADWIND STRONG HEADWIND	> -8 0 to -10 -5 to +10 5 to +30 > +25

[4] For airports with multiple runways, each runway is assessed separately.

		Crosswind (including gust)	knots	LIGHT MODERATE STRONG	0 to 15 10 to 30 > 25
		Runway slope	%	SHALLOW MODERATE STEEP	< 2 1.5 to 4 > 3
		Proximity to off-site medical facilities	km	VERY CLOSE NEAR FAR	< 10 5 to 50 > 40
General		Heading change	degrees	LOW MEDIUM HIGH	0 to 55 40 to 120 > 100
		Aircraft weight	kg	LIGHT AVERAGE HEAVY	< 50,000 45,000 to 66,000 > 63,000
		Number of persons[5]	people	LOW MEDIUM HIGH	< 50 30 to 150 130 to 180

C. Fuzzy Rules

In addition to the fuzzy input variables and fuzzy sets, fuzzy rules were defined as a result of discussions with airline pilots. These fuzzy rules make it possible to associate a risk profile to each candidate landing site for every combination of the fuzzy input variables of each emergency flight segment. A total of 1495 rules were defined and Table 3 gives a snapshot of these rules. For example, in the Descent fuzzy logic sub-system, IF (‘Vertical terrain/obstacle clearance’ is MEDIUM) AND (‘Horizontal thunderstorm clearance (upwind)’ is HIGH), THEN ‘Descent risk’ is MEDIUM. Similarly, in the General fuzzy logic sub-system, IF (‘Heading change’ is MEDIUM) AND (‘Aircraft weight’ is AVERAGE) AND (‘Number of persons’ is HIGH), THEN ‘General risk’ is HIGH.

The fuzzy rules attempt to capture the logic used by pilots when assessing the risks associated with a particular landing site. They also attempt to encode the priority (weighting) of different variables in a particular emergency flight segment; for example, in the Landing segment, runway length has a higher priority than proximity to off-site medical facilities. Furthermore, the fuzzy rules account for complementary risk factors (fuzzy input variables) such as:

- ‘Runway length’ and ‘Runway surface friction’ (e.g. a LONG runway can compensate for POOR runway surface friction);
- ‘Visibility’ and ‘Instrument approach’ (e.g. GOOD instrument approach facilities – with ILS, etc. – can compensate for LOW visibility);
- ‘Runway length’ and ‘Headwind’ (e.g. a STRONG headwind can compensate for a SHORT runway).

The output (risk score) of each fuzzy logic sub-system was defined to have three fuzzy sets (LOW, MEDIUM and HIGH), with the exception of the Overall fuzzy logic sub-system, which was defined to have five fuzzy sets (VERY LOW, LOW, MEDIUM, HIGH, and VERY HIGH). The additional fuzzy sets of the Overall sub-system increase the sensitivity of the framework to differences in risk between candidate landing sites. A mix of shapes was selected for the membership functions of the output (risk score) of each fuzzy logic sub-system; trapezoidal shapes were chosen for the outermost membership functions whereas triangular shapes were chosen for the inner membership function(s). Centroid defuzzification is performed in this study to convert the output risk profile to a single crisp value. This method locates the center of the area of the aggregated fuzzy set and returns the corresponding value.

[5] Persons on-board (including passengers and crew).

Table 3. A sample of the fuzzy rules of the proposed fuzzy logic framework

Emergency flight segment		**Input variables (aka linguistic variables)**	**Input fuzzy set(s)**	**Output fuzzy set (Perceived risk)**
Descent		Vertical terrain/obstacle clearance	MEDIUM	MEDIUM
		Horizontal thunderstorm clearance (upwind)	HIGH	
Approach		Vertical terrain/obstacle clearance	HIGH	LOW
		Horizontal thunderstorm clearance (upwind)	HIGH	
		Population density	LOW	
		Visibility	HIGH	
		Cloud cover	LOW	
Landing	Conventional landing sites (airports)	Runway length	SHORT	HIGH
		Runway width	AVERAGE	
		Runway surface friction (Runway Condition Code)	POOR	
		Airport facilities	ADEQUATE	
		Instrument approach	GOOD	
		Visibility	HIGH	
	All landing sites	Horizontal distance to landing site	NEAR	
		Headwind/tailwind	LIGHT WIND	
		Crosswind (including gust)	STRONG	
		Runway slope	SHALLOW	
		Proximity to off-site medical facilities	NEAR	
General		Heading change	MEDIUM	HIGH
		Aircraft weight	AVERAGE	
		Number of persons	HIGH	
Overall		Descent risk	MEDIUM	HIGH
		Approach risk	LOW	
		Landing risk	HIGH	
		General risk	HIGH	

IV. Preliminary Validation of Fuzzy Logic Framework

A hypothetical forced landing scenario was defined to evaluate the suitability of the proposed fuzzy logic framework for emergency landing site selection. In this scenario, an Airbus A320 aircraft is cruising at an altitude of 35,000 feet Above Mean Sea Level (AMSL) when a dual-engine failure occurs, resulting in TLOT. From this altitude, it is assumed that four conventional landing sites (runways) are within the glide footprint of the damaged aircraft as shown in Figure 4. The position and orientation of the runways relative to the aircraft, the wind direction for each runway, and the glide footprint are all shown to scale. The glide footprint of the aircraft was determined using the methods presented in [13], [19]. Moreover, it is assumed that: all runways are at sea level; each runway has only one landing direction; the aircraft can reach each runway by following the dashed path and dissipating any excess energy (using spoilers, landing gear, etc.); and all systems (apart from the engines) are functioning normally.

The scenario was defined such that it is not immediately obvious which runway is the most suitable, or how the runways should be ranked. Table 4 summarizes the key pros and cons of each candidate runway, whereas Table 5 shows the values of the fuzzy input variables for each candidate runway. Table 6 shows the risk computed by the fuzzy logic framework for each flight segment, as well as the overall risk associated with each candidate landing site.

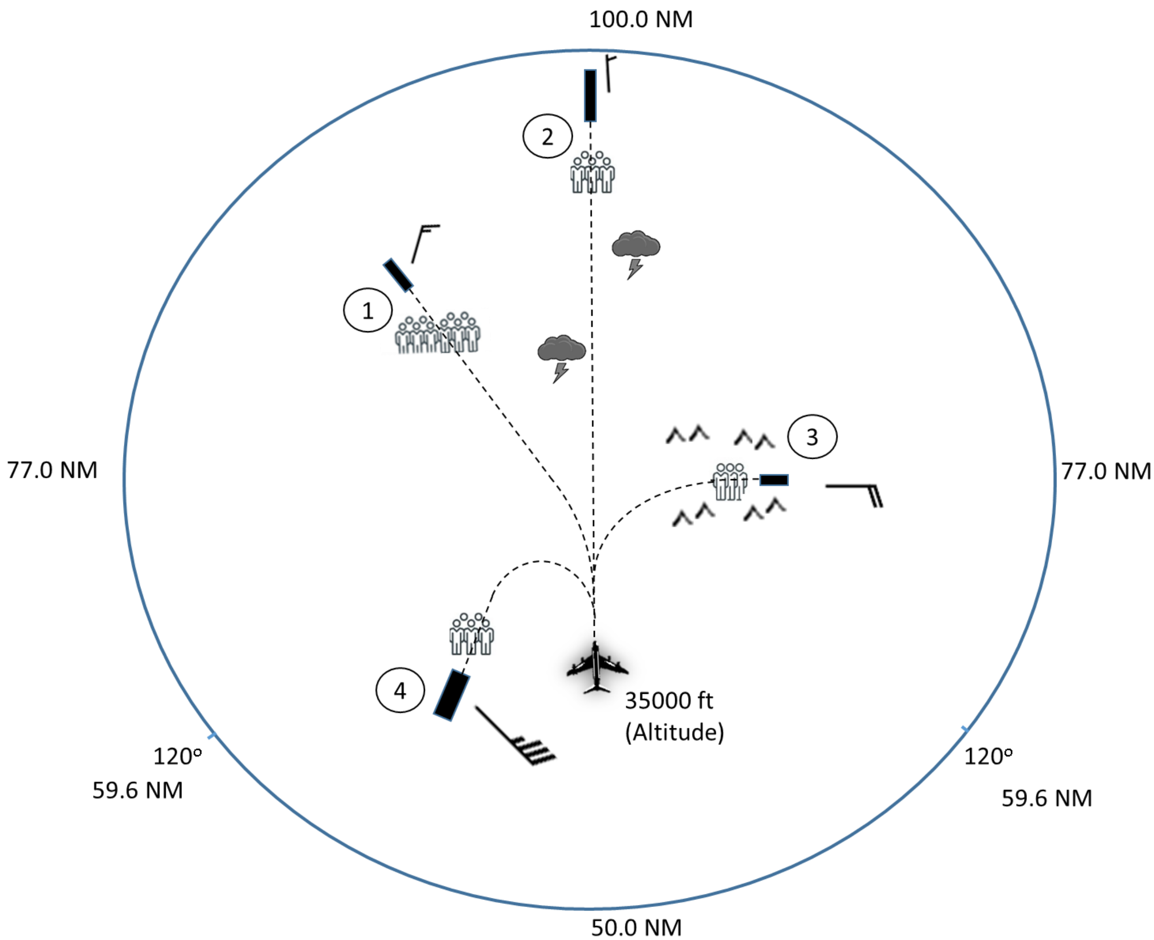

Fig. 4 Hypothetical forced landing scenario.

Table 4. Summary of pros and cons of each runway considered in the test scenario

	Runway 1	Runway 2	Runway 3	Runway 4
Pros	• Relatively far from terrain/obstacles and hazardous weather • High visibility • Good instrument approach facilities • Close to medical facilities	• Directly ahead of aircraft • Relatively far from terrain/obstacles • Long runway • Good instrument approach facilities • Close to medical facilities	• Relatively far from hazardous weather • Low population density along the landing route • Good runway surface friction • Moderate headwind • Good airport facilities • Well within the gliding distance of the aircraft	• Relatively far from terrain/obstacles and hazardous weather • High visibility • Long and wide runway • Relatively close to aircraft • Good instrument approach facilities • Close to medical facilities
Cons	• High population density along the landing route • Light to moderate crosswind	• Relatively close to thunderstorms • Low visibility • Close to the edge of the glide range of the aircraft	• Relatively close to terrain/obstacles • Short runway	• Situated behind the aircraft • Poor/medium runway surface friction • Moderate/strong crosswind

Table 5. Inputs of the fuzzy logic framework

Phase	Input variables (aka linguistic variables)	Units	Runway 1	Runway 2	Runway 3	Runway 4
			Value	Value	Value	Value
			Fuzzy set(s)	Fuzzy set(s)	Fuzzy set(s)	Fuzzy set(s)
Descent	Vertical terrain/obstacle clearance	feet	2000	2000	1000	2000
			MEDIUM/ HIGH	MEDIUM/ HIGH	LOW	MEDIUM/ HIGH
	Horizontal thunderstorm clearance (upwind)	nautical miles	30	4	30	30
			HIGH	LOW/ MEDIUM	HIGH	HIGH
Approach	Vertical terrain/obstacle clearance	feet	2000	2000	1000	2000
			MEDIUM/ HIGH	MEDIUM/ HIGH	LOW	MEDIUM/ HIGH
	Horizontal thunderstorm clearance (upwind)	nautical miles	30	4	30	30
			HIGH	LOW/ MEDIUM	HIGH	HIGH
	Population density	number of people per km^2	27000	12000	5000	12000
			MEDIUM/ HIGH	LOW/ MEDIUM	LOW	LOW/ MEDIUM
	Visibility	meters	10000	500	2000	10000
			HIGH	LOW	MEDIUM	HIGH
	Cloud cover	oktas	1	1	1	1

				LOW	LOW	LOW	LOW
Landing	Conventional landing sites (airports)	Runway length	meters	1850	3000	1500	3000
				AVERAGE	LONG	SHORT	LONG
		Runway width	meters	44	44	44	50
				AVERAGE	AVERAGE	AVERAGE	WIDE
		Runway surface friction	-	4	4	6	2
				MEDIUM/ GOOD	MEDIUM/ GOOD	GOOD	POOR/ MEDIUM
		Airport facilities	-	50	50	80	50
				ADEQUATE	ADEQUATE	GOOD	ADEQUATE
		Instrument approach	-	90	90	50	90
				GOOD	GOOD	ADEQUATE	GOOD
		Visibility	meters	10000	500	4000	10000
				HIGH	LOW	MEDIUM	HIGH
	All landing sites	Horizontal distance to landing site	-	0.7	0.9	0.35	0.5
				NEAR/FAR	FAR	VERY CLOSE/ NEAR	NEAR
		Headwind/ tailwind (including gust)	knots	4	4	20	20
				LIGHT WIND	LIGHT WIND	MODERATE HEADWIND	MODERATE HEADWIND
		Crosswind (including gust)	knots	12	0	0	26
				LIGHT/ MODERATE	LIGHT	LIGHT	MODERATE/ STRONG
		Runway slope	%	1	1	1	1
				SHALLOW	SHALLOW	SHALLOW	SHALLOW
		Proximity to off-site medical facilities	km	9	9	20	9
				VERY CLOSE/ NEAR	VERY CLOSE/ NEAR	NEAR	VERY CLOSE/ NEAR
General		Heading change	degrees	45	0	90	130
				LOW/ MEDIUM	LOW	MEDIUM	HIGH
		Aircraft weight	kg	55,000	55,000	55,000	55,000
				AVERAGE	AVERAGE	AVERAGE	AVERAGE
		Number of persons	people	140	140	140	140
				MEDIUM/ HIGH	MEDIUM/ HIGH	MEDIUM/ HIGH	MEDIUM/ HIGH

Table 6. Risk assessment of the candidate landing sites

		Runway 1		Runway 2		Runway 3		Runway 4	
		Phasewise Risk	Overall Risk	Phasewise Risk	Overall Risk	Phasewise Risk	Overall Risk	Phasewise Risk	Overall Risk
Overall risk	Descent	0.5 (M)	0.6022 (H)	0.8147368 (H)	0.68076 (H)	0.823852 (H)	0.6861 (H)	0.5 (M)	0.6629 (H)
	Approach	0.63284 (H)		0.8072195 (H)		0.814737 (H)		0.292476 (L)	
	Landing	0.67014 (H)		0.6705372 (H)		0.5 (M)		0.610133 (H)	
	General	0.71161 (H)		0.711614 (H)		0.711614 (H)		0.809915 (H)	
Rank	-	1		3		4		2	

When compared to the other runways, the Descent phase risk values for Runways 2 and 3 are much higher due to weather hazards (in the case of Runway 2) and terrain hazards (in the case of Runway 3). In the Approach phase, Runway 4 has the lowest risk value, mainly because the path to this runway is clear of weather and terrain hazards. On the other hand, the other runways have a HIGH approach risk value due to their proximity to thunderstorms or terrain. Runway 3 is assigned the lowest risk value during the Landing phase, mainly due to its GOOD runway surface friction, GOOD airport facilities, VERY CLOSE/ NEAR horizontal distance to landing site, MODERATE headwind and LIGHT crosswind. The General fuzzy logic sub-system assigns the highest risk to Runway 4. This is because, although Runway 4 is the closest runway, a LARGE heading change would be required to align the aircraft with this runway. According to the proposed fuzzy logic framework, Runway 1 is the safest option (lowest risk), followed by Runways 4, 2 and 3.

The test scenario defined in this section was presented to an airline captain – with over 20 years of experience – in order to obtain his personal interpretation of the risks associated with each landing site. No prior indication of the results obtained with the proposed framework was provided to the pilot in order to avoid biasing him. The pilot carefully considered the values defined in Table 5 and concluded that Runway 1 would be the best option, followed by Runway 4, Runway 3 and, finally, Runway 2. Thus, it can be observed that Runways 2 and 3 were ranked differently by the pilot and the proposed framework. This might indicate that further tuning of the proposed framework is warranted, or that the overall risk of Runway 2 is very similar to that of Runway 3 (as implied by the results obtained with the proposed framework), such that the ranking of these two runways becomes highly subjective. In any case, such results may, however, enable this study to fine-tune the parameters such that the output replicates better the pilot's assessment.

From this initial expert assessment, some critical feedback was obtained. One main point that was discussed at length was the initial altitude of the aircraft as this will dictate how certain risk factors are perceived by the crew. For instance, if initial altitude is adequate, then the system could associate certain weightings to the input factors such that these are ranked based on perceived risk. In this case, the horizontal thunderstorm clearance (upwind) in the Descent and Approach phases would be more critical than the vertical terrain/obstacle clearance. This is because, from a pilot's perspective, the approach path for a conventional runway would have been designed in such a way to allow for adequate vertical clearance along the entire path. Furthermore, terrain is fixed whereas weather is dynamic (it could be moving, it could deteriorate rapidly, etc.). Therefore, weather is less predictable and pilots would be more concerned about weather. Terrain would become more of an issue below 10,000 feet AMSL. Based on the same argument, if the aircraft can follow the standard approach path, then population density is also not a critical factor in selecting a runway. According to the pilot, the order in which the risk factors should be prioritised for the Approach segment should be as follows (starting with the highest priority risk factor): horizontal thunderstorm clearance (upwind), visibility, cloud cover, vertical terrain/obstacle clearance, and population density.

Another point that was discussed is that instrument approach is not critical because the aircraft will probably not be able to follow the glideslope. In this case, the ability to visually monitor the path becomes crucial and therefore good visibility is more desirable. On the other hand, horizontal guidance would be beneficial on approach. Additionally, runway length is more important than having a runway approach aid such as ILS.

V. Conclusions and Future Work

This paper proposed a fuzzy rule-based approach to assist the flight crew to rank suitable conventional landing sites during an emergency landing of a commercial passenger aircraft. The emergency landing is divided into four phases – descent, approach, landing, and general – and a fuzzy logic sub-system is defined for each phase. The risk associated with each phase is determined for each potential landing site, followed by an estimation of the overall risk of each landing site. The candidate landing sites are then ranked on the basis of their overall risk and presented to the crew for further consideration.

Future research will include more extensive validation of the proposed system through discussions with the airline pilot community, as well as the study and incorporation of unconventional landing sites into the current model. The design of an accurate trajectory generator is also seen as a critical task in providing on-board support during emergency landing situations.

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