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# HARVIS: dynamic rerouting assistant using deep learning techniques for Single Pilot Operations (SPO)

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**Abstract**

When a diversion due to an emergency is required in flight, and especially in SOP operations during the approach and landing phases, the pilot's workload increases considerably. To help gathering the relevant information and calculating the new alternative flight paths, we developed a digital assistant for dynamic rerouting, which uses deep learning algorithms to calculate the new trajectories for landing based on data collected from previous flights and METAR information. This AI assistant would be capable of improving pilots' decision-making when a rerouting is required. The re-routing assistant HMI prototype was developed and validated in feedback sessions with pilots, Advisory Board workshops with several stakeholders and a human-in-the-loop with 8 professional pilots at ENAC A320 research simulator. The concept of the assistant was appraised positively, although an effort is still to be done to improve the overall interaction and interface with the assistant to obtain some benefits in terms of workload. Aspects such as workload, usability, trust and explainability and training are analysed and discussed in the results.



*Keywords:* Artificial intelligence; deep learning; dynamic rerouting; pilot decision support tool; human in the loop simulation.

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## 1. Introduction

In the past decade, the growth of air traffic has been continuous, even after Covid-19, and it is expected to keep increasing in the upcoming years, according to IATA's 20 Year Passenger Forecast (IATA, 2021), the total passenger numbers to/from/within Europe are expected to reach 86% of 2019 values in 2022, before making a full recovery in 2024 (105%). In the case of traffic to/from/within North America, it is expected to continue to perform strongly in 2022 as the US domestic market returns to pre-crisis trends, and with ongoing improvements in international travel. In 2022, passenger numbers will reach 94% of 2019 levels, and full recovery is expected in 2023 (102%), ahead of other regions. Traffic to/from/within Latin America is forecast to see a strong 2022, passenger numbers are forecast to be surpassed in 2023 for Central America (102%), followed by South America in 2024 (103%) and the Caribbean in 2025 (101%).

In addition to this, the world is facing a pilot shortage after Covid-19, according to Oliver Wyman consulting firm scenarios (Murray, 2022), the root cause varies by region, from mandatory retirement and barriers to entry due to the high cost of training or recruitment policies of airlines. They state that based on a modest recovery scenario from Covid-19 crisis, a global pilot shortage will emerge in certain regions no later than 2023 and most probably before. However, with a more rapid recovery and greater supply shocks, this could be felt as early as today. Regarding magnitude, they estimate a global gap of 34,000 pilots by 2025. This could be as high as 50,000 in the most extreme prediction.

Forecasts like these, together with economic savings and advances in automation and AI applications, have been bringing Single Pilots Operations (SPO) into focus for the past times (Myers, 2021), (Bailey, Kramer, Kennedy, Stephens, & Etherington, 2017) and what a few years ago was seen as a distant future, has actually become a reality in Europe: EASA has already published the AI Roadmap (EASA, 2020) and an associated Concept Paper on Level 1 machine learning applications (EASA, 2021), which will be further developed to include the provisions for more advanced types of AI (level 2 AI applications), involving a higher degree of collaboration and even teaming between the human end user and the AI-based systems. They have also an ongoing project which deals with the approval of machine learning (ML) technology for systems intended for use in safety-related applications (EASA, 2022) and are about to launch a project to assess the risks of the main changes induced by the Extended Minimum Crew Operations (eMCO) and SPO operations while considering a series of changes to aircraft cockpit configuration identified for large Commercial Air Transport (CAT) aircraft and including new flight management applications (EASA, 2022).

In this context, it is clear that the use of digital assistants for supporting both the pilots and the ground operators will be indispensable for SPO to be successful (Wolter & Gore, 2015). When analysing the tasks which increase notably both pilots and air traffic management workload, we have identified the case of diversion to an alternative airport when in-flight emergencies occur, said emergencies range from engine failures, on board smoke or fire, medical situations to unexpected weather conditions. In the case of SPO, these situations turn out into an especially sensitive issue.

As part of HARVIS project (HARVIS, 2021), we propose the implementation of a digital assistant capable of monitor the aircraft status and flight conditions to detect the emergency and calculate the trajectories to the possible alternative airports. Presenting all the relevant information to the pilot in a centralised and synthetic way through an HMI installed in the pilot's flight bag. Our aim is to analyse the impact of having such assistant in the cockpit supporting the decision-making process during high-workload and stressful situations for the pilots in SPO, as the absence of a pilot monitoring in such situations leaves all the workload to the pilot flying.

## 2. Dynamic rerouting assistant

A diversion is often required during high workload situations like severe system failures, a sick passenger, or for meteorological reasons (dense fog, storms, etc.). In conventional operations when a diversion is needed, the pilot in command and first officer discuss on the multiple options they have and reach the best solution together on the based on several parameters. The role of the digital assistant will be similar to the one of the second pilot: It will take into account characteristics of nearby airports, the METAR at destination, the facilities to take care of passengers, among other factors. It may then propose several options to the pilot, they will be ranked and the benefits and drawbacks for each of them will be presented.

### *2.1. Assistant overview*

The assistant developed takes into account the aircraft status (location, heading, speed, engine parameters and fuel consumption); the characteristics of nearby airports (location, category, types of approach, runways' information and maintenance hangar); the Meteorological Aerodrome Report (METAR) at destination, the Terminal Area Forecast (TAF) report and the facilities to take care of sick passengers.

It calculates the trajectories to the surrounding airports and proposes a ranking of possible landing options to the pilot. The benefits and drawbacks for each one will be highlighted by colour coding the relevant values. Once the pilot has all the information, he/she will be able to make the final decision.

The workload associated to the rerouting should be reduced, allowing the pilot to focus on flying the aircraft safely and handling other critical tasks such as mitigating the consequences of a system failure.

The assistant has a visual/auditory Human-Machine Interface that shows not only the information mentioned above, but also will allow the pilot to interact with the assistant in a verbal or tactile way to ask for details about each alternative, so that it can support him/her during the decision-making process in case of diversion, by providing all the required information. The design was refined after gathering feedback from experts in a dedicated session, the implementation of the changes suggested led to the current version. This assistant considers two different categories for the emergencies:

- *Light emergency:* This situation is not time restricted, so the assistant will show further information for the pilot to make the best decision. In this sense many factors such as trajectory, fuel, infrastructure, weather, etc. will be considered. Additionally, an artificial intelligence algorithm is used here, which will provide the pilot with a prediction of the most likely landing runway, as well as an approaching and landing route to the new airport based on the experience of previous flights obtaining through a web-scrapping algorithm in charge of downloading the training data into tabular structured files (the METAR reports have been obtained from the Mesonet website (Mesonet, 2020) and the trajectory information has been downloaded from the FlightRadar24 website (FlightRadar24, 2020)). This AI algorithm uses two different tools:
    - A classification algorithm using a neural network able to predict the landing runway using the METAR information 30 minutes before landing: An ensemble of Multi-Layer Perceptron (MLP) models for estimating the best Terminal Arrival Point (TAP) depending on the METAR data at the destination airport was designed and implemented.
    - A regression algorithm which, once the runway has been predicted, will evaluate the trajectory of the aircraft and provide the flight path. Therefore, taking as starting point the aircraft's position and as final target the TAP's coordinates, a Flight Trajectory Estimation was performed by a Convolutional Long Short-Term Memory Neural Network (CNN-LSTM). This way, the position at future timesteps is predicted based on the position of the aircraft in previous timesteps and the information learned from historical data of previous flights.
- *Severe emergency:* In this situation it is expected that ATC will understand the type of emergency, separate the aircraft from surrounding traffic and inform the landing aerodrome about the situation, while the assistant will support the pilot's decision-making process by providing all the possibilities and the feasible trajectories calculated. In this case, the solution adopted for the algorithm is inspired by RRT* (Rapidly-exploring Random Tree) method ( (Knispel & Matousek, 2013)) and based on Dubins curves ( (Shkel & Lumelsky, 2001)) for the aircraft trajectories. RRT* proved to provide good enough solutions rapidly in an open search space as is aerial navigation, building up a search tree that fills the space omnidirectionally and with sufficient density to connect it to the entry points to the final approach of the runways that stay within the range of the aircraft.

Right after the emergency has been detected and properly notified by the assistant, it will calculate the alternative trajectories through the methods previously described, evaluate them and display the information from these options as a list in the HMI. This list is prioritised according to different optimisation parameters previously defined such as flight distance, time or fuel consumption, weather conditions, runway length, the available infrastructures at the location, etc.

Once all the alternatives have been presented to the pilot (Figure 1), he/she will be able to interact with the assistant to request details about them (e.g. flight distance, estimated arrival time, weather conditions at the destination, etc.) and to modify the optimisation parameters to reorder the alternatives. The interaction modality can be via touchscreen or using through voice commands.

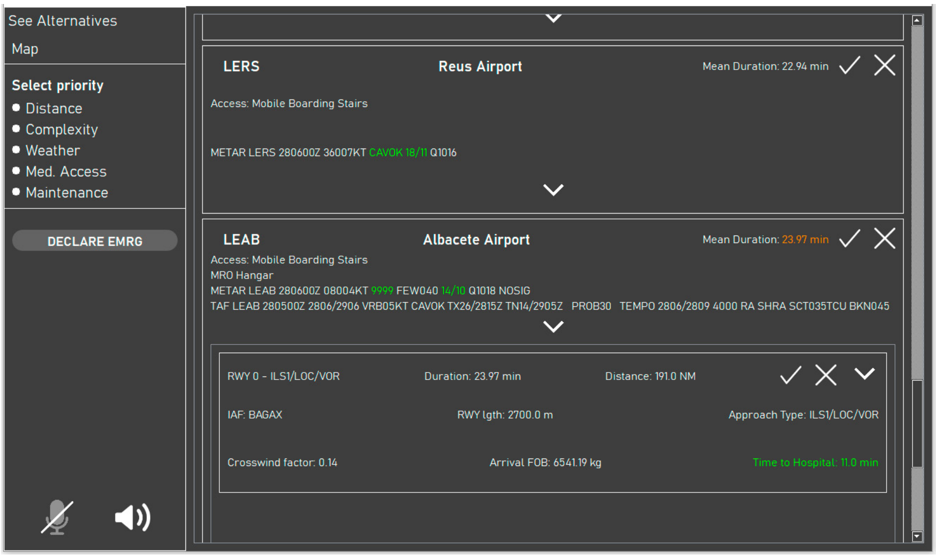


Figure 1: Rerouting assistant main menu: alternatives airport presented

## 3. Validation sessions

The assistant was installed in a tablet and located in the left side of the cockpit, on the pilot's flight bag (Figure 2) in ENAC's A320 research simulator. During the validation sessions, two scenarios were presented to each one of the 8 pilots participating in the experiments, both during the flight Malaga-Munich. In the first one, a single engine failure was automatically detected by the assistant, whilst in the second, a medical emergency was declared so the pilot could inform the assistant about it and request for alternative landing options.

Figure 2: Assistant placement in the cockpit simulator

For each test, the pilots were informed about the initial flight plan, the flight conditions, weather and initial location of the aircraft. Once the emergency was detected, the interaction with the assistant started and the pilots were able to ask for the necessary information.

After having presented the alternatives based on the information onboard, each pilot decided the final landing option from the ones selected, which concluded the experiment.

## 4. Participants

Eight professional pilots participated in the experiment. They were informed about the general aim of the research goals and their consents were gathered. The anonymity of their responses has been ensured and the French Personal Data Protection Code was respected. The project was approved by the Ethics Commission for Research of the University of Toulouse (project 2021-394). All participants were male. Four participants had Captain experience whereas the other four had only First Officer experience, the average flight experience was 5537 hours with a standard deviation of 4318. They all received a briefing about the cockpit simulator and the assistant interface.

## 5. Measurements

Feedback from the pilots was collected via post simulation questionnaire and debriefing sessions. Figure 3, shows the list of questions used. Additionally, over-the-shoulder observations were made by experts during the sessions to collect insights about the pilot's performance, including aspects related to experienced workload, situation awareness, usability, faced difficulties, recovery actions, safety related events, etc. The methods and techniques used for the validation sessions were designed by the consortium experts as part of HARVIS project's Validation Plan (EC, 2022).

| | | 1 | 2 | 3 | 4 | 5 | N/A |
|---|---|---|---|---|---|---|---|
| General | 1.1 The assistant is useful | | | | | | |
| | 1.2 The information presented for each airport is adequate | | | | | | |
| | 1.3 The assistant improved my decision-making | | | | | | |
| | 1.4 The assistant supported me in accomplishing my tasks in a timely and accurate manner | | | | | | |
| Trust | 2.1 The assistant works accurately | | | | | | |
| | 2.2 I am confident in working with the system | | | | | | |
| | 2.3 I trust the assistant | | | | | | |
| | 2.4 I understand what the system is doing and why | | | | | | |
| Usability | 3.1 The system is easy to use | | | | | | |
| | 3.2 The information displayed by the assistant is clear | | | | | | |
| | 3.3 The symbology (icons) is easy to understand | | | | | | |
| | 3.4 The colour coding is consistent with the cockpit philosophy | | | | | | |
| Acceptability | 4. Would you like to use the assistant in operations (Y/N): | | | | | | |
| | If not, please explain why not: | | | | | | |

**General overview**

- Apart from these, which types of emergencies do you consider should be detected and alerted to the pilots?

**Human Machine Interaction**

- How do you consider the assistant is compared to a PM since it is doing the same task as the PM?
- Are there any differences in the type of support considering this task?
- Would you consider using voice commands to with the assistant in an emergency situation?

**Explainability vs workload balance**

- Is it easy to understand the criteria based on which the alternatives are prioritized? (Transparency)
- Are this criteria useful? Do they summarize the main criteria based on which you would make a decision on which airport to take?

**Trust**

- Can you think about any aspects that could improve your trust in the information presented by the assistant?

Figure 3: Questionnaire (1=Strongly disagree, 2 = Disagree, 3 = Neither agree not disagree, 4 = Agree, 5 = Strongly agree) and debriefing points used in the debriefing after the validation sessions to collect pilot's feedback

## 6. Results

### 6.1. Overall opinion and acceptability

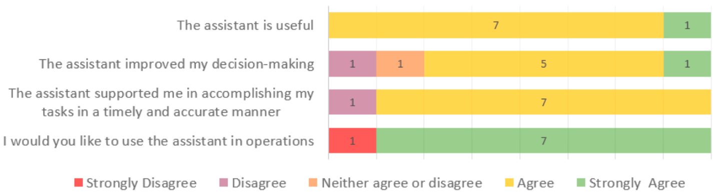


Figure 4: Overall opinion

In general terms, the assistant was praised positively by pilots, specifically, the concept in which it has been based. The assistant was considered useful, all pilots agreed (Figure 4). Regarding the support during the decision-making process and the tasks performance, 7 out of 8 pilots agreed that they would use it in operations, the remaining one stated that although he would like to use such kind of assistant, we would not use it in its current design. A common opinion was that the information should be presented in a more concise and user-friendly way, to avoid overloading the pilot with information. The parameters presented, their location and the criteria used to colour-code them should be modified to simplify the interaction.

When discussing the role of the assistant, pilots commented that, although the assistant can process more information and in less time than a pilot monitoring (PM), it misses an interpretative layer, as it just presents raw information and does not challenge the pilot's opinion and reasons for choosing one alternative over another. Thus, when a pilot is supported by the assistant instead of a PM, he or she needs to interpret a lot of information and lacks the possibility of engaging in a discussion.

### 6.2. Decision-making process evaluation

During the scenarios, both, the time taken by the pilots to choose the alternative once the emergency was declared and the landing option selected for each scenario, were collected as metrics for decision-making performance indicator.

In the first scenario, it took the pilots a mean time of 4:37 min to decide which alternative to choose, whereas the mean time was of 3:37 min in the second one. This indicates that the time consumed is quite short when compared with the traditional process. After ensuring the safety of the flight and communicating the emergency to the ATC, pilots normally have to check first which alternatives they have and then ask the ATC or the airline for information, compare all data, discuss the options and make a decision (with the help of the copilot). The time for gathering information was reduced thanks to the assistant making available and centralising all the information required and avoiding the need of requesting meteorological reports or airports details one by one.

During the first scenario (Single Engine Failure), one pilot chose to land at the alternative presented by the assistant as first option. Two of them selected the second and third options respectively, as they were both close and had good weather conditions and the runways were longer that the one at the first option, as they preferred to have a bigger runway to reduce the risk when landing with one inoperative engine.

Two pilots decided to go a bit further to airports indicating that they had maintenance repair and overhaul (MRO) Hangars, which was a priority for them and also because they knew the airports and felt more confident landing there.

Finally, the remaining one considered the single engine failure not to be a very serious emergency, as it still allows to fly safely and decided to go further until finding a big airport, where it was sure to find mechanical assistance for the aircraft.

For the second scenario (Medical emergency onboard), one pilot decided to go to the closest alternative. Another two selected airports which were close enough and had good weather and another identified three possible locations: one, because he considered that it would be easier to get medical attention for the sick passenger landing at a bigger airport, and the rest because he knew the airports and thought it would be easier for them to land there. After narrowing the options, he said he would need to discuss it with the authorities and the airline before deciding where to go.

Finally, the remaining four pilots decided to go to a further airport which they considered that, being a big airport, they would have the facilities and emergency assistance required to quickly attend the sick passenger and they would have enough time during the flight there to inform the ATC and authorities about the details of the emergency.

In both cases, when asked about what alternative they would have chosen if no assistant was used, only 3 pilots gave a direct answer, as they already knew the airports and they were close enough according to the Navigation Display. The other 5 pilots did not give an answer, as they indicated they needed more data to evaluate their options based on a discussion with the ATC or the airline instructions and assistance to gather the information.

### *6.3. Workload vs explainability evaluation, usability and trust*

In terms of explainability, during the debriefing sessions, although the pilots appreciated that the assistant integrates useful information, they mentioned that it displays too much data leading to increased workload. Pilots commented that it would be better to reduce the number of presented alternatives on the HMI. Additionally, half of the pilots said that they would prefer a more visual interface to decrease the complexity of the presented information, e.g.: Instead of, or in addition to the list view, a map view with elevations, airport labels and flight trajectory representations were suggested to be added.

Additionally, information such as weather can be presented more visually by using icons, in order to further decrease mental workload. In contrast, three pilots indicated that a map would not make a difference to them. One of the pilots mentioned that it would be nice if the alternatives would be integrated in the existing navigation display. Another pilot believed that a map could be useful for pilots that are not familiar with the area or that are less experienced.

In order to make it easier to choose an alternative airport, apart from reducing the number of alternatives presented one pilot also mentioned that it would be good to use the criteria to filter and reduce the number of alternatives. When there is less information to present, the size of the information can be increased to further improve the assistant's usability.

Regarding the usability of the system (Figure 5), most of them agreed with the way in which the assistant presents the information to the pilots, who generally understood it, but found it difficult to process it efficiently in order to make the best decision.

In terms of trust (Figure 6), although most of the pilots were confident with the system and understood how it was working, many of them did not completely agree with the way it works right now, comments such as the ability to keep the information updated through the flight and changes in the way of presenting it were suggested. When asked, generally, the pilots indicated that they trusted the assistant. Some reported that their trust could be improved by learning more about the process behind the information that is presented, the reliability and the recency of the information.

With regard to the alternatives selected by each pilot, after discussing it during the debriefing sessions with them, it was noticed that the experience of the pilots and their knowledge of the area played an important role when choosing an airport for landing, as well as in the information or reasons that they consider as primary when choosing a landing alternative. More experienced pilots who were already familiar with the surrounding airports were able to make a decision more easily and quickly than pilots with less experience or those who were not familiar with the area, who needed more time to check and compare the characteristics of the different available options presented.

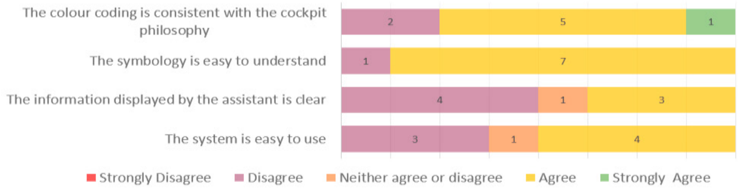


Figure 6: Usability of the assistant

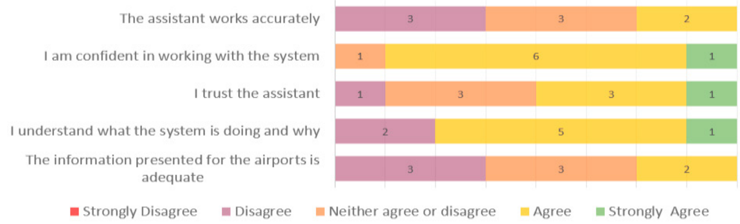


Figure 6: Trust in the assistant

## 7. Discussion and conclusion

As can be observed from the validation session outcomes, the assistant developed still requires further iterations in order to better support pilots in operations. For this reason, the first step would be to implement the suggested changes to improve the current version of the assistant. These changes would include modifications in the visualization of the information such as reducing the list of alternatives, bringing forward the most important parameters, including settings to customize and rearrange the information, ensuring that the information presented is constantly being updated during the flight, (especially the weather information, through an internet connection for example), etc.

In addition to this, airlines' internal information and policies, such as preferred locations or any additional data about the airports and the airline operations in them, could also be included and be considered as input for presenting the alternatives.

In this line, when displaying the selection of airports to the pilot based on the priority, more information has to be taken into account when presenting the alternatives, such as the amount of traffic around those airports and additional details and indications from ground (runways closed, landing systems inoperative) to support the final decision.

As another future development, it would be useful for the assistant to be able to modify the information presented in the HMI or the actions suggested to the pilots according to the workload or stress level detected while monitoring them, simplifying it and displaying only the most relevant details to help them focus and prioritize and avoiding overloading the pilots.

Finally, when thinking ahead about a future integration in cockpits, to generalise the assistant to be used in civil flight operations, the information from all the airports has to be included in the assistant database and kept regularly updated. For the prototype, these data were gathered manually looking into the Spanish (ENAIRE, s.f.) and French (FRANE, s.f.) AIP documentation available in their website, so it should be necessary to find an alternative way to get all these parameters more easily (using web-scrapping technics or involving database providers (Navblue, s.f.), for example). In the same way, the weather information in the area of interest will have to be collected regularly during the flight, this will probably require an internet connection that keeps it updated in the local database.

Regarding the AI algorithms that predict the trajectories for the rerouting, more variables to define the landing conditions such as the crosswind information and parameters to characterise the runway (orientation, infrastructures available, traffic density, etc.) will need to be included as variables for the training so they can be applicable to all airports. Additional variables should also be considered to improve the trajectory prediction, such as the flight plan information, weather conditions in the surroundings or economic factors. Moreover, in order to generalise the algorithms to allow the estimation of aircraft trajectories with independence of the destination airport, a change of paradigm from the current data-driven model to a reinforced learning methodology could be explored.

This would be a challenge as the algorithms have to be learning during the flight, but it could be helpful, especially for SPO, to add more parameters keeping in mind to make it too complex and avoid increasing the computational load excessively. One concern raised while consulting experts during the sessions with the Advisory Board meetings was that making the algorithms more complex will also imply additional considerations in terms of explainability, so pilots are aware of what and how information has been used for selecting the best alternatives (even at a training phase).

Additionally, it would be interesting to study more deeply how the assistant can support the decision besides the gathering of the information, using additional algorithms for giving the trade-off, as in a two-member cockpit crew, when it comes to making the decision after gathering the information, there is a good effort of criticism during the selection which is not currently implemented in the assistant.

A question that remained is how to address the request of making the assistant cooperation "more human-like" and capable of holding a discussion or customising the amount of information provided to the pilot after monitoring their status will affect trust, acceptance and explainability and how to deal a complex tool be certified for aviation.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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