Safety Risk Assessment in Aircraft Fuel Planning and Management

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By

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Abstract

In this report we demonstrate the outcomes of the research performed in the Air Transport Safety Institute of the Royal Netherlands Aerospace Centre (NLR). This research project constitutes the MSc Thesis of the writer, towards the graduation of the MSc Aerospace Engineering at Delft University of Technology (Air Transport & Operations).

The subject of this project lies in the area of aviation safety and quantitative risk assessment. In specific, the study deals with the safety issue of fuel planning and fuel management in airlines' operations (Commercial Air Transport).

As the air traffic growths rapidly, it is a challenge to keep the current safety levels and further improve them, achieving the EU's vision safety target, which is less than one accident per ten million flights by 2050. Amongst the various accidents and incidents categories, this project researches the accidents and incidents related to fuel. In specific, we investigate two fuel-related events; the probability of a flight landing with less than the minimum regulated fuel amount (called FRF - Final Reserve Fuel) and the probability of fuel exhaustion.

So as to analyse and assess the safety risks, we followed the steps of the TOPAZ methodology. Based on previous research on the subject, an extensive hazards list was created, as well as an agent-based risk model was developed and implemented as a Stochastic Dynamically Coloured Petri Nets (SDCPN) model. The risk model was algorithmically implemented in JAVA programming language, in the direction of conducting Monte Carlo simulations. The first's event (FRF) probabilities were estimated through regular (straightforward) Monte Carlo simulation, whilst for the second (fuel exhaustion) regular Monte Carlo proved to be insufficient. Indeed, fuel exhaustion is a rare event and, consequently, an acceleration method was needed to be implemented. The acceleration method chosen is the Interacting Particle System (IPS).

Finally, through the simulations, we estimate the probabilities of these rare events for several operational scenarios. The fuel-related risks were assessed for their acceptability, eventually proving that for all scenarios the risks are either tolerable or acceptable, while also the most prominent safety bottlenecks are identified and analysed.

Preface

This report represents my MSc Thesis for the Master of Science in Aerospace Engineering degree at Delft University of Technology. The MSc thesis was performed in Air Transport Safety Institute of the Royal Netherlands Aerospace Centre (NLR), in the form of a graduate internship.

For the successful completion of this thesis I was privileged to be guided by scientists and experts in the field of aviation safety. I would like to grab the opportunity to thank them all.

First, I want to express my gratitude to Dr. Sybert Stroeve, my daily supervisor at NLR. His knowledge, guidance, patience, and positive attitude during the internship was of utmost importance for the successful realization of the project. I would also like to thank my TU Delft supervisor, Prof. Henk Blom; his great experience and knowledge about aviation safety were determinant on the writing of this thesis. Finally, special thanks to NLR scientist Bert Bakker for his considerable guidance on the implementation of the acceleration method.

In closing, I would like to thank my family and friends who supported me in this long journey.

Stefanos Mazaris
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Acronyms

ACARE	Aviation Research and Innovation in Europe
AGL	Above Ground Level
AMC	Acceptable Means of Compliance
APU	Auxiliary Power Unit
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATM	Air Traffic Management
ATS	Air Traffic Service
CFIT	Controlled Flight Into Terrain
CAT	Commercial Air Transport
CDL	Configuration Deviation List
DP	Decision Point
EASA	European Union Aviation Safety Agency
EDTO	Extended Diversion Time Operations
ERA	En-Route Alternate (aerodrome)
ETOPS	Extended Range Twin Engine Operations
FAA	Federal Aviation Administration
FRF	Final Reserve Fuel
GM	Guidance Material
ICAO	Internation Civil Aviation Organization
IFR	Instrument Flight Rules
IPS	Interacting Particle System
ISA	International Standard Atmosphere
LOC	Loss Of Control
MC	Monte Carlo
MEL	Minimum Equipment List
NOTAM	Notice to Airmen
NPA	Notice of Proposed Amendments
OFP	Operational Flight Plan
PF	Pilot Flying
PNF	Pilot Not Flying
SARPs	Standards And Recommended Practices
SESAR	Single European Sky ATM Research
SMM	Safety Management Manual
TOPAZ	Traffic Organization and Perturbation AnalyZer

1 Introduction

While aviation is evolving with an unprecedented pace, with analysts to predict double the traffic by 2035 [1], aviation safety levels are considered to be the highest ever; the current fatal accidents rate is indeed the lowest ever in Commercial Air Transport (CAT) [2]. As traffic growths, it is a challenge to keep the same safety levels or even improve them. Indeed, a lot of research projects and programs (NextGen in the USA, SESAR in the European Union) are running to accommodate the forecasted traffic, while simultaneously achieve EU's vision safety target, which is less than one accident per ten million flights by 2050 [3]; This is a significant improvement on the current rates, which lie around 1.35 jet hull losses per 1 million flights [4].

Sometimes, at the expense of safety, airlines struggle to optimise their operations in the direction of reducing costs; as the most substantial expenditure for the airlines is fuel (around the one-third of the total expenses [5]), pressure is put on airlines to become more fuel-efficient. One of the ways implemented by airlines to reduce fuel consumption is to minimise the amount of extra fuel taken on board [6], which is not intended to be used. This fuel is taken for any unpredicted case that may arise during the flight, at the discretion of the pilot-in-command (PIC), after judging the special requirements of a specific flight. In particular, as the fuel consumption of an aeroplane is directly connected to its weight, a fuel load increase leads to consumption increase. Moreover, less fuel intake could allow more passengers and cargo accommodation, so some tons of fuel not taken could be translated into some extra revenue.

Efficient execution of flights, in terms of fuel consumption, requires the precise knowledge of the flight duration. Notwithstanding the current technological developments, fuel predictions are not flawlessly precise and accurate, due to the fact that they are based on anticipated (and forecasted) conditions and imperfect models of aeroplanes' performance; as such, determining the appropriate fuel quantity is governed by uncertainty. This uncertainty is caused by various unpredictable factors that affect flight time. Delays during taxi, cruise or approach, adverse weather or other natural phenomena, flight planning mistakes and malfunctions are some factors which can profoundly and unpredictably disturb the flight time. Eventually, if the fuel uplift is under-calculated, the flight is likely to be required to divert to an alternate airport, which is operationally disruptive and costly, or, even worse, to risk with fuel exhaustion, as occurred with LaMia Flight 2933 [7].

This pressure for better fuel efficiency through carrying less fuel on-board in combination with the uncertain nature of the flight time (e.g. due to unpredicted delays, weather phenomena or airport closures) and possible fuel system malfunctions, may provoke low-fuel circumstances while the aeroplane is flying. At that point, pilots' decision making is of utmost importance [6], as they have to decide over the need to land to an alternate (closer) airport, rather than the intended destination. Consequently, the pilots are performing an implicit risk assessment for the remaining fuel adequacy.

Organization of the thesis

The thesis is organized in two volumes. The first volume includes chapters 1-6, while the second volume includes the four appendices. Our study starts with Chapter 2, which includes the presentation of the various fuel planning and management regulations, as published by the major rule-making bodies. The objective of Chapter 2 is to locate, summarize, present and compare the most important aviation organizations' regulations; moreover, regulations for special types of operations are considered and presented. In particular, the amount of fuel that an aircraft should carry is regulated for all Instrument Flight Rules (IFR) flights by the International Civil Aviation Organization (ICAO). As a result, a little room is given to airlines to optimise the amount of fuel intake. The regulations also prescribe that all IFR flights should land with an amount of fuel above a certain threshold; this amount is called the Final Reserve Fuel (FRF) and is set to thirty minutes of flight time. If an aeroplane lands with an amount of fuel less than this threshold (FRF), the situation is considered as an incident. This event is the first safety concern and motivation of this study; namely, to assess the risk of landing with less than the FRF. The second concern of this study is the fuel exhaustion event, which happens when an aircraft runs out of fuel while flying. This situation, which inevitably leads to all engines off state, is an extremely dangerous situation which has led repetitively to crashes and several fatalities [8]. As such, fuel exhaustion will be the second event to be assessed for risks.

Next, in Chapter 3, we present the method employed towards conducting the safety risk assessment of the two aforementioned events, namely the Traffic Organization and Perturbation AnalyZer (TOPAZ) [9]. TOPAZ has successfully been employed for safety assessment in various and different types of operations, mainly in the aviation sector, but also others. TOPAZ consists of eight steps, from which the first four steps are included in this Chapter: we set our objectives and we also describe the operations that will be considered, we perform the hazard identification while the Chapter finishes with the description of the constructed scenarios.

In Chapter 4, as part of the safety risk assessment according to TOPAZ methodology, a risk model is developed and presented (TOPAZ step 4). In specific, in the direction of realizing the quantitative probabilities estimation, an agent-based risk model was developed and implemented as a Stochastic Dynamically Coloured Petri Nets (SDCPN) model; the risk model was implemented in JAVA programming language, to conduct Monte Carlo simulations. The first's event (FRF) probabilities were estimated through regular (straightforward) Monte Carlo simulation, whilst for the second (fuel exhaustion), regular Monte Carlo proved to be not sufficient. Indeed, fuel exhaustion is a very rare event and, hence, an acceleration method needed to be implemented. The acceleration method chosen is the Interacting Particle System (IPS). In closing, this chapter includes the high-level description of the risk model, a brief presentation of the implementation into a computer program, the development of the simulation acceleration method, the verification and the validation processes.

In Chapter 5, the three final steps of the safety risk assessment (following the TOPAZ method) are presented. Starting with the probability evaluation of the three main scenarios, we present the results of the Monte Carlo simulation runs for all scenarios. Then, we evaluate the acceptability of the probabilities' estimation, based on the severity considered in Chapter 3. Finally, the safety risk tolerability assessment section includes our analysis on the risk acceptance and at last, we analyse the bottlenecks, as identified during the simulations. Finally, Chapter 6 includes the overall conclusions of this research project, as well as matters of discussions and suggestions.

In the second volume of the thesis, four appendices are presented. In Appendix A we present the Initial hazards list. In Appendix B and Appendix C, the developed hazards lists before clustering and after clustering are presented, respectively. Finally, in Appendix D, the Stochastic Dynamic Coloured Petri Net model is demonstrated.

2 Aircraft’s Fuel Management and Planning Regulations

In this Chapter we are summarizing and discussing the various fuel-related regulations, imposed by the major aviation rulemaking organisations. Fuel planning is a highly regulated area in the world of aviation. Indeed, this is why the current Chapter is of utmost importance for the project: Flight dispatchers and pilots fuel up the aircraft according to these regulations. The differences amongst the various regulations will be explored, while also some particular scenarios and fuel cases will be covered. As a norm followed in the current Chapter, the regulations are presented in black coloured boxes.

2.1 International Civil Aviation Organization (ICAO)

The International Civil Aviation Organization (ICAO), which is a United Nations Agency, is the most important civil aviation organisation in the world, counting a total of 192 member states [10]. The organisation has published nineteen Annexes (to the Convention of International Civil Aviation), which can be characterised as the aviation “Bible”, as all member states generally follow.

ICAO is the organisation that first regulated the fuel quantity that an aeroplane should carry. As ICAO describes in Doc. 9976 Fuel Planning and Fuel Management Manual in paragraph 2.2, the origins of the previous Annex 6, Part I fuel provisions lie at the end of the first half of the previous century. In the 1950s, the meteorological forecasts were inaccurate and unreliable, the fuel use was almost unpredictable, and support from dispatchers or operations control was, many times, totally inexistent.

The new aviation era brought the computerised flight planning and the flight management systems (FMS), increasing the accuracy, as well as the predictability of fuel planning. These systems also provide analysis capabilities based on actual and forecasted conditions. Fuel consumption based on statistics programs substantially contributes to predicting fuel burn and contingency fuel amounts. Alternate airport selection and fuel planning methods have also significantly evolved, and advanced in-flight monitoring provides defences against safety risks whilst also provide increased operational efficiency. All these new developments have significantly increased operational reliability, leading to safer operations and mitigating fuel-related hazards. Indeed, fuel events are considered of low occurrence and are not included in the top aviation hazards in Commercial Air Transport (CAT) category [11].

In Annex 6, Part 1, paragraph 4.3.6 *Fuel Requirements*, general directions on the fuel planning of air carriers are given. Starting with generic requirements such as ”*An aeroplane shall carry a sufficient amount of usable fuel to complete the planned flight safely and to allow for deviations from the planned operation.*” and continuing with possible operating conditions that a flight may deal with and affect its flight time. Such conditions include Notices to Airmen (NOTAM), meteorological reports and forecasts, Air Traffic Service (ATS) procedures, restrictions, anticipated delays, the effects of deferred maintenance items and configuration deviations. The previously mentioned factors render fuel planning an elaborate and multivariate process. ICAO also defines more precisely the fuel requirements for a flight. These requirements are considered to be of utmost importance for this study. According to this paragraph, there are seven main fuel categories which should be considered in-flight fuel planning. These fuel categories are summarised in the following box.

In the last part of the paragraph, it is stated that the State of the Operator may, based on the

- ***Taxi fuel*** The amount of fuel expected to be consumed before take-off.
- ***Trip fuel*** The amount of fuel required to enable the aeroplane to fly from take-off until landing at the destination aerodrome, taking into account the operating conditions.
- ***Contingency fuel*** The amount of fuel required to compensate for unforeseen factors. It shall be 5% of the planned trip fuel, but not lower than the amount required to fly for 5 minutes at holding speed at 1500ft above the destination aerodrome in standard conditions.
- ***Destination alternate fuel*** The amount of fuel needed to perform a missed approach at the destination aerodrome, climb to the expected cruising altitude, fly the expected routing, descend to the point where the expected approach is initiated and conduct the approach and landing at the destination alternate aerodrome.

  * Where two destination alternate aerodromes are required, the amount of fuel, in addition to the aforementioned in the bullet, should enable the aeroplane to proceed to the destination alternate aerodrome which requires the greater amount of alternate fuel.

  ** If flight is operated without a destination alternate aerodrome, the amount of fuel required is such that enables the aeroplane to fly for 15 minutes at holding speed at 1500ft above the destination aerodrome elevation in standard conditions.

  ***There is one more case that the rule maker is taking special care of, where the aerodrome of intended landing is an isolated aerodrome. In this case, for a jet aeroplane, the amount of fuel required is for two hours at normal cruise consumption above the destination aerodrome, including final reserve fuel.
- ***Final reserve fuel*** The amount of fuel calculated using the estimated mass on arrival at the destination alternate aerodrome, or the destination aerodrome when no destination alternate aerodrome is required. For a jet aeroplane, the amount of fuel required to fly for 30 minutes at holding speed at 1500ft above aerodrome elevation in standard conditions.
- ***Additional fuel*** The supplementary amount of fuel required if the minimum fuel calculated, as described in all the categories above, is not sufficient to allow the aeroplane to descend as necessary and proceed to an alternate aerodrome in the event of engine failure or loss of pressurization, whichever requires the greater amount of fuel based on the assumption that such a failure occurs at the most critical point along the route **or** fly for 15 minutes at holding speed at 1500ft above aerodrome elevation in standard conditions and make an approach and landing.
- ***Discretionary fuel*** The extra amount of fuel to be carried at the discretion of the pilot-in-command.

results of a specific safety risk assessment conducted by the operator, approve variations to the pre-flight fuel calculation of taxi fuel, trip fuel, contingency fuel, destination alternate fuel, and additional fuel. ICAO also allows, under specified circumstances and acceptance by the local authority, the operator to deviate from the regulation, after proposing an alternative fuel plan. Apart from the fuel requirements paragraph, Annex 6 defines the In-flight fuel management requirements. In the respective paragraph, the operator’s obligation to establish fuel policies and procedures is described, while also many pilots’ obligations are listed.

Furthermore, Annex 6, Part I, 4.3.7.1 requirements include that operators should establish policies and procedures to ensure that in-flight fuel checks and fuel management is performed by the flight crew. Operator policies and procedures typically require that at regular intervals the pilots should compare actual vs planned fuel consumption, verifying the fuel quantity used against the fuel quantity expected to be used up to that point.

Finally, ICAO Doc. 9976 *Flight Planning and Fuel Management Manual* (FPFMM) is a separate publication by the Organization concerning the aircraft fuel planning and management requirements. While Annex 6, Part I provide the basis for fuel planning and fuel management regulations, however, does not provide details, for States and operators, for the selection of alternate aerodromes or the carriage of fuel based on the implementation of either method. In this manual such provisions are described, as well as many details over the implementation of the fuel regulations by various rulemaking agencies are provided. In addition, performance-based and prescriptive compliance with fuel regulations (e.g. EDTO operations) is presented in paragraph 2.4.

In closing, some conclusions over the ICAO provisions may be deducted. ICAO was the first organisation to define various the various fuel types needed for the planning of a flight, providing clear plane definitions for them. Also, the newer publication Doc. 9976 provides several compliance alternatives for the member States, introducing modern concepts such as performance-based compliance, something out of the scope of this project. ICAO provisions will serve as a basis for the rest of our regulations study, as it will be attempted to find, present and compare the major aviation rulemaking agencies fuel-related legislation.

2.2 European Union’s Aviation Safety Agency (EASA)

The European Aviation Safety Agency is the centrepiece of the European Union's strategy for aviation safety. The Agency’s mission is to promote the highest common standards of safety and environmental protection in civil aviation. The Agency develops common safety rules at the European level, by drafting aviation safety legislation and providing technical advice to the European Commission and the 32 Member States.

Commission Regulation (EU) No 965/2012 describes the technical requirements and administrative procedures related to air operations (EU-OPS) pursuant to Regulation (EC) No 216/2008 of the European Parliament and the Council. Studying the Acceptable Means of

Compliance (AMC) and Guidance Material (GM) to Annex IV Commercial air transport operations [Part-CAT] the fuel regulations imposed by the Agency may be found. In this section, the fuel planning regulation will be presented, and deviations from the ICAO set standards will be explored. Finally, literature research for the EASA new regulation proposals (Notice of Proposed Amendments-NPA) is conducted.

In paragraph OP.MPA.150 (b) Fuel policy of [12] the Agency dictates, in line with ICAO, the fuel planning criteria. In order not to duplicate, as they have been already referred in section 2.1, only differences will be presented in the box below.

- **Taxi fuel** EASA introduces considerations in taxi fuel, in specific "Local *conditions at the departure aerodrome and auxiliary power unit (APU) consumption should be taken into account."*
- **Trip fuel** EASA introduces many specific considerations in its calculation, such as "taking into account the expected departure routing, "including any step climb/descent", "taking into account the expected arrival procedure".
- **Contingency fuel** Many specifications are set by the regulator about the contingency fuel. In specific, it is ruled that this fuel should be the higher of the following, but not less an amount to fly for 5 minutes at holding speed at 1500ft, above the destination aerodrome in standard conditions.
  (A) 5 % of the planned trip fuel.
  (B) Not less than 3 % of the planned trip fuel, provided that an En-route Alternate (ERA) is available.
- **Alternate fuel** In line with ICAO specifications with only additional considerations set by the Agency about the planning, which should be done with consideration to the complete missed approach and departure procedures

*Final reserve fuel, minimum additional fuel and Extra fuel are in line with ICAO

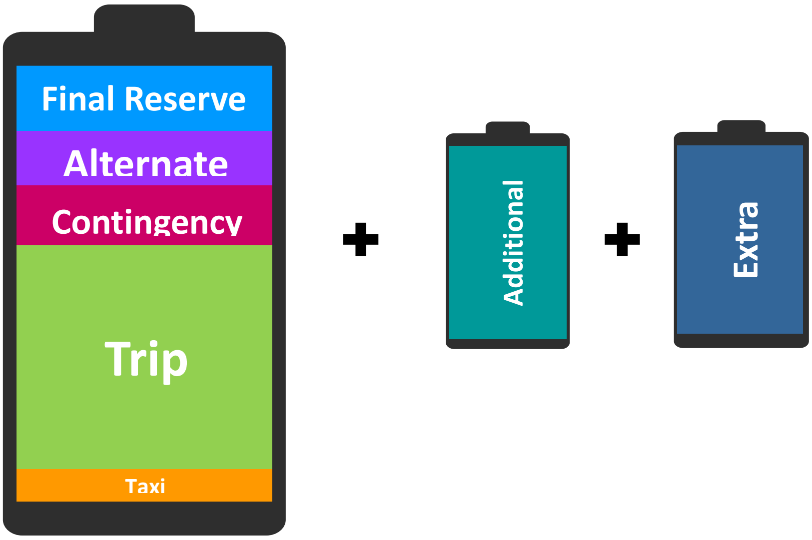


Figure 1 The fuel required for Commercial aeroplane flights by EASA, in line with ICAO Annex 6

EASA Proposal for Amendments

EASA publishes Notices of Proposed Amendment (NPA) to propose an amendment in the existing regulations, giving time to the interested parties to consider it and raise objections or recommendations. Notice of Proposed Amendment 2016-06 (A) *Fuel planning and management* makes many suggestions and observations, where the most important and related to this project are presented below. The following proposed amendments are included in [13]. In [12] (paragraph MPA.181(c)), it is stated that throughout the years, it has been identified that some European operators have been constantly using less-than-required fuel for the taxi, causing the use of contingency fuel during the taxi phase of flight. This practice brings a safety reduction and unfair competition, hence increasing risk in favour of lowering operational costs. To avoid arbitrary interpretation by European airlines, which brings a reduction to safety, EASA redefined the contingency and taxi fuel definitions.

As such, the redefinition proposal for taxi fuel states that it should consider the local conditions at the departure airport, including at least the published NOTAM, the meteorological conditions, the air traffic services procedures and known delays. The redefinition proposal for the contingency fuel states that Pilot in Command should perform a reanalysis and an adjustment of the planned trip, and, if necessary, return to the parking for refuelling, if delays result in the consumption of contingency fuel before take-off. The use of contingency fuel during taxiing prior to take-off is permitted only if extraordinary situations would bring long ground delays.

Next, in [12] (in paragraph MPA.183), EASA specifies the need for alternate airports, regarding Instrument Flight Rules flights. Analysing the prescriptive requirements of [12], there should be two selected alternates airports when the destination is below weather minima from one hour before to one hour after (hence, not available) the expected arrival time, one alternate when the destination is available (same time periods), no alternates provided that two runways are available and certain meteorological conditions are fulfilled from 1 h before to 1 h after. The requirements indicate the safety aim: two landing options available at the time of reaching the arrival airport.

2.3 Federal Aviation Administration (FAA)

Federal Aviation Administration (FAA) employs an entirely different approach to fuel planning regulations. Starting with regulation *14 CFR PART 121.OPERATING REQUIREMENTS: DOMESTIC, FLAG AND SUPPLEMENTAL OPERATIONS, Subpart U. Dispatching and Flight Release Rules, Section 121.645. Fuel supply: Turbine-engine powered aeroplanes, other than turbo propeller*, we find that:

14 CFR § 121.639 Fuel supply: All domestic operations.
No person may dispatch or take off an airplane unless it has enough fuel
(a) To fly to the airport to which it is dispatched
(b) Thereafter, to fly to and land at the most distant alternate airport (where required) for the airport to which dispatched
(c) Thereafter, to fly for 45 minutes at normal cruising fuel consumption [...]

For the next regulation paragraph, two definitions are needed to be provided:

Flag operation: Any scheduled operation conducted by [...] turbojet aeroplanes [...] at the following locations between any point within the U.S. […] and any point outside the U.S. or between any point outside the U.S. and another point outside the U.S.
Supplemental operations: Non-Domestic and Non-Flag operations (mostly non-scheduled and charter).

§ 121.645 Fuel supply: Turbine-engine powered airplanes, other than turbo propeller: Flag and supplemental operations.
(a) Any flag operation within the 48 contiguous United States and the District of Columbia may use the fuel requirements of § 121.639.
(b) For any certificate holder conducting flag or supplemental operations outside the 48 contiguous United States and the District of Columbia [..] a turbine-engine powered airplane [..] considering wind and other weather conditions expected, should have enough fuel
(1) To fly to and land at the airport to which it is released
(2) After that, to fly for a period of 10 percent of the total time required to fly from the airport of departure to, and land at, the airport to which it was released
(3) After that, to fly to and land at the most distant alternate airport specified in the flight release, if an alternate is required, and
(4) After that, to fly for 30 minutes at holding speed at 1,500 feet above the alternate airport (or the destination airport if no alternate is required) under standard temperature conditions.
(c) No turbine-engine powered airplane [..] should take off if an alternate is not specified [..] unless it has enough fuel, considering conditions expected, to fly to that airport and thereafter to fly for at least two hours at normal cruising fuel consumption.

§ 121.646 En-route fuel supply: flag and supplemental operations.

(a) No turbine-engine powered airplane with more than two engines for a flight more than 90 minutes should take off unless:

(1) The airplane has enough fuel to meet the requirements of § 121.645(b)

(2) The airplane has enough fuel to fly to the Adequate Airport

(i) Assuming a rapid decompression at the most critical point

(ii) Assuming a descent to a safe altitude in compliance with the oxygen supply requirements

(iii) Considering expected wind and other weather conditions.

(3) The airplane has enough fuel to hold for 15 minutes at 1500 feet above field elevation and conduct a normal approach and landing.

Conclusions

Commenting on FAA fuel planning regulations, FAA introduces a different fuel planning regulatory framework, which can be characterised as simpler than this of EASA. Besides, we notice that FAA uses a different fuel regulatory approach between the domestic (within the 48 contiguous United States) and non-domestic flights. Referring to the first category, no analytic and separate directions for the fuel use are given. This simplified and less strictly regulated form of fuel legislation may provide the opportunity to the operators to become more fuel-efficient and judge the fuel uplift based more on their discretion.

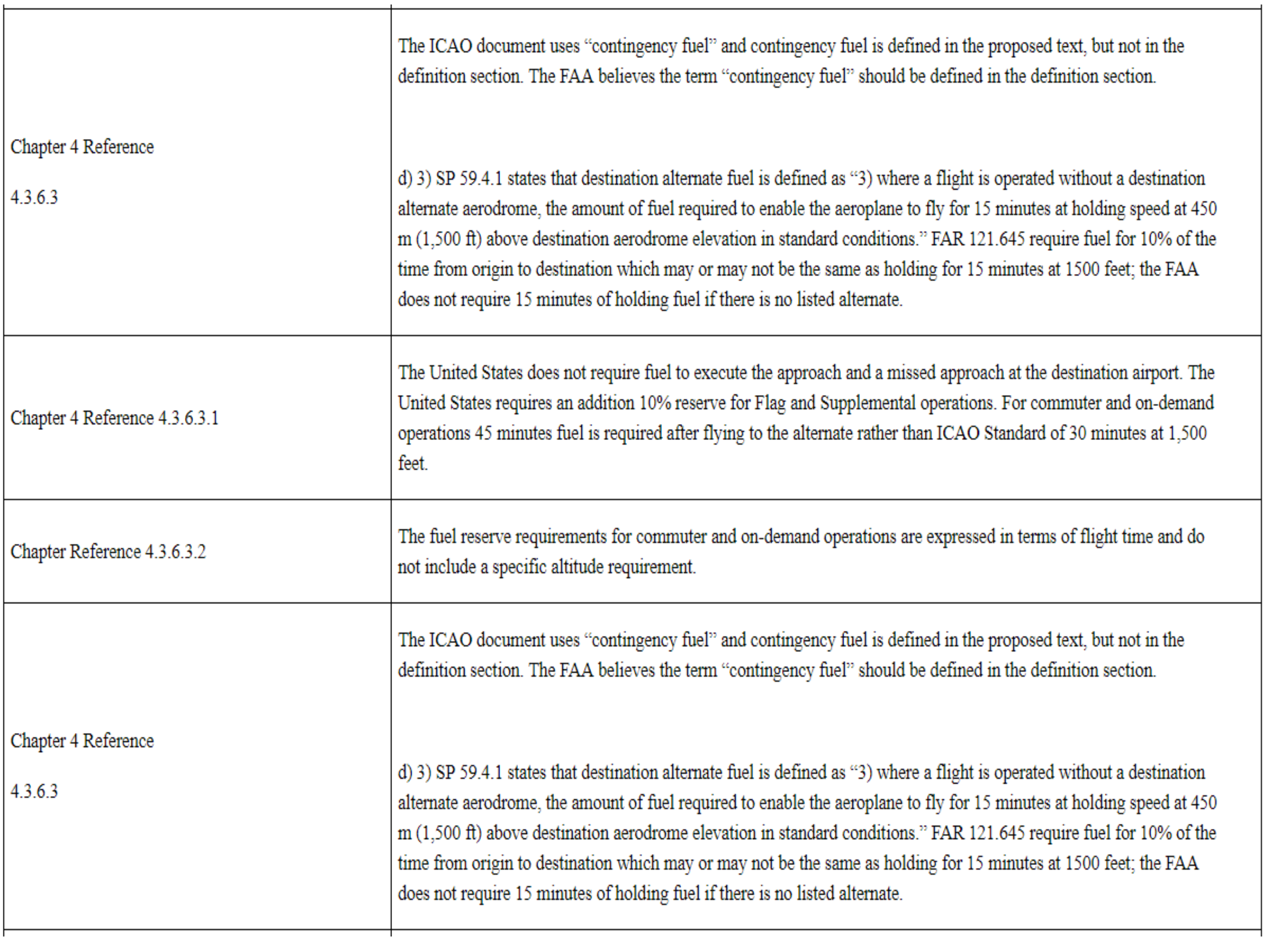
Considering the paragraph FAA regulation paragraph 121.645(b), which provides the fuel regulations of the second category, (outside the 48 contiguous states) the fuel uplift becomes more regulated than before, providing directions on additional and alternate fuel, without though naming them. Despite that, in neither case, ICAO terminology is employed, concerning the fuel allocated for the various flight phases (taxi, contingency, alternate, discretionary etc.).

Finally, the deviation from the ICAO Annex 6 follows from the fact that ICAO provisions on fuel are Standards And Recommended Practices (SARPs). SARPs do not have the same legal binding force as the Convention itself, because Annexes are not international treaties. In case that a State deviates from the ICAO SARPs, have to publish the difference in a particular part of its Aeronautical Information Publication (AIP), namely part “GEN”, under the section “Differences From ICAO Standards, Recommended Practices and Procedures”. FAA clearly states in [14], section GEN 1.7, the differences from ICAO Annex 4, part of which can be found in Table 1.

In this section only jet aeroplanes related regulations have been presented. It is also essential to notice the difference between the fuel regulations imposed for domestic flights (within the 48 contiguous States) and the rest of the flights. This probably arises from the airport infrastructure availability in the United States. Despite FAR 121 does not provide fuel management rules, according to Airbus [15], airlines usually implement the following rules in their operating manual.

As it describes, the minimum quantity of remaining fuel at landing (alternate or destination) is normally equivalent to the final reserve, namely fuel quantity necessary to fly for a period of 30 to 45 minutes at 1.500 feet Above Ground Level at holding speed in International Standard Atmosphere conditions.

Table 1 Differences From ICAO Standards, Recommended Practices and Procedures [14]



Chapter 4 Reference 4.3.6.3	The ICAO document uses "contingency fuel" and contingency fuel is defined in the proposed text, but not in the definition section. The FAA believes the term "contingency fuel" should be defined in the definition section. d) 3) SP 59.4.1 states that destination alternate fuel is defined as "3) where a flight is operated without a destination alternate aerodrome, the amount of fuel required to enable the aeroplane to fly for 15 minutes at holding speed at 450 m (1,500 ft) above destination aerodrome elevation in standard conditions." FAR 121.645 require fuel for 10% of the time from origin to destination which may or may not be the same as holding for 15 minutes at 1500 feet; the FAA does not require 15 minutes of holding fuel if there is no listed alternate.
Chapter 4 Reference 4.3.6.3.1	The United States does not require fuel to execute the approach and a missed approach at the destination airport. The United States requires an addition 10% reserve for Flag and Supplemental operations. For commuter and on-demand operations 45 minutes fuel is required after flying to the alternate rather than ICAO Standard of 30 minutes at 1,500 feet.
Chapter Reference 4.3.6.3.2	The fuel reserve requirements for commuter and on-demand operations are expressed in terms of flight time and do not include a specific altitude requirement.
Chapter 4 Reference 4.3.6.3	The ICAO document uses "contingency fuel" and contingency fuel is defined in the proposed text, but not in the definition section. The FAA believes the term "contingency fuel" should be defined in the definition section. d) 3) SP 59.4.1 states that destination alternate fuel is defined as "3) where a flight is operated without a destination alternate aerodrome, the amount of fuel required to enable the aeroplane to fly for 15 minutes at holding speed at 450 m (1,500 ft) above destination aerodrome elevation in standard conditions." FAR 121.645 require fuel for 10% of the time from origin to destination which may or may not be the same as holding for 15 minutes at 1500 feet; the FAA does not require 15 minutes of holding fuel if there is no listed alternate.

2.4 Special Operations

In this section, the special cases regulations will be covered. By special cases are meant specific types of flights that require a different fuel planning approach. The regulators have recognised the unique nature of those flight operations and have introduced special regulations, which will be presented below. The reason for covering this aspect of the operations is that it is believed to be of special interest in terms of fuel planning and management.

Extended Range Twin Engine Operations (ETOPS), Extended Diversion Time Operations (EDTO) and Long-Range Operations (LROPS)

ETOPS, EDTO and LROPS are special types of operations which are of high interest in terms of fuel planning. These kinds of operations are generally long-haul flights for which particular flight planning criteria and requirements are applied. EDTO provisions for aeroplanes with two turbine engines do not differ from the provisions for extended range operations by aeroplanes with two turbine engines (ETOPS). Therefore, EDTO may be referred to as ETOPS. ICAO [16] introduced the Extended Diversion Time Operations (EDTO) regime in place of ETOPS. Despite that, the EDTO regime has been widely accepted, the term EDTO has not. The term ETOPS has been retained by FAA and others by redefining it as an abbreviation for 'ExTended range OPerationS' instead of 'Extended range Twin OPerationS'. EASA continues to use ETOPS as originally defined and 'LROPS' (Long Range OPerationS) for extended range operation by more than two engines aircraft [17]. All the differences are summarised and presented in Table 2 below. In this report, we will be referring to ETOPS as defined by EASA.

Table 2 Summary of the special operations' names

Organisation	**ICAO**	**EASA**		**FAA**
Acronym	EDTO	ETOPS	LROPS	ETOPS
Type of operations	Extended Diversion Time Operations	Extended Twin OPerationS	Long Range OPerationS	ExTended OPerationS
Applicability	Aeroplanes with two or more engines	Aeroplanes with two engines	Aeroplanes with more than two engines	Aeroplanes with two or more engines

ETOPS are flights that may operate further than one hour from a diversion airport at the one-engine inoperative cruise speed, over water or remote lands. Those routes were previously restricted to more than two engines aircraft [18]. The development of modern twinjet aircraft has driven the authorities to revise the old rules. These modern rules benefit from the unprecedented performance and safety levels of today's two-engine aircraft. ETOPS acronym is followed by a number, indicating the number of minutes that the specific aircraft is allowed to perform such operations, limiting its distance from the furthest alternate airport. This number varied from 75 min in the past, to 90,120,180 and more than 180 today [19]. Recently EASA certified [20] Airbus A350 XWB for up to 370 minutes ETOPS, the longest ETOPS ever certified. In the figure below we illustrate the difference between an ETOPS flight route (green line) and anon-ETOPS flight route (blue-dashed line). In the non-ETOPS flight routing, the aeroplanes should deviate from the shortest path between departure and arrival airports. This happens to comply with the regulations imposing a maximum distance from the en-route alternate. On the other side, an ETOPS flight can follow a shortest (or the shortest) path, keeping a greater distance from the en-route alternate airports.

The ETOPS operations regulations by FAA order that no *ETOPS* flight may take-off unless, taking into consideration the wind and the weather, has enough fuel to satisfy each of the requirements presented in the following box. It should be noted that EASA regulations coincide with those of FAA presented below, and thus will not be presented separately.

(1) Fuel to fly to an ETOPS Alternate Airport.

(i) [..] The airplane must carry the greater of the following amounts of fuel:

(A) Fuel sufficient to fly to an ETOPS Alternate Airport assuming a rapid decompression at the most critical point followed by descent to a safe altitude in compliance with the oxygen supply requirements.

(B) Fuel sufficient to fly to an ETOPS Alternate Airport (at the one-engine-inoperative cruise speed) assuming a rapid decompression and a simultaneous engine failure at the most critical point followed by descent to a safe altitude in compliance with the oxygen requirements .

(C) Fuel sufficient to fly to an ETOPS Alternate Airport (at the one engine inoperative cruise speed) assuming an engine failure at the most critical point followed by descent to the one engine inoperative cruise altitude.

(ii) Fuel to account for errors in wind forecasting. In calculating the amount of fuel required by paragraph (1)(i), increase the actual forecast wind speed by 5% to account for any potential errors in wind forecasting.

(iii) Fuel to account for icing. In calculating the amount of fuel required by paragraph (1)(i),(ii), the airplane should carry the greater of the following amounts of fuel in anticipation of possible icing during the diversion:

(A) Fuel that would be burned as a result of airframe icing during 10 % of the time icing is forecast (including the fuel used by engine and wing anti-ice during this period).

(B) Fuel that would be used for engine anti-ice, and if appropriate wing anti-ice, for the entire time during which icing is forecast.

(iv) Fuel to account for engine deterioration. In calculating the amount of fuel required before, the airplane also carries fuel equal to 5% of the fuel specified above, to account for deterioration in cruise fuel burn performance unless the certificate holder has a program to monitor airplane in-service deterioration to cruise fuel burn performance.

(2) Fuel to account for holding, approach, and landing. In addition to the fuel required by paragraph (1), the airplane must carry fuel sufficient to hold at 1500ft above field elevation for 15 minutes upon reaching an ETOPS Alternate Airport and then conduct an instrument approach and land.

(3) Fuel to account for APU (Auxiliary Power Unit) use.

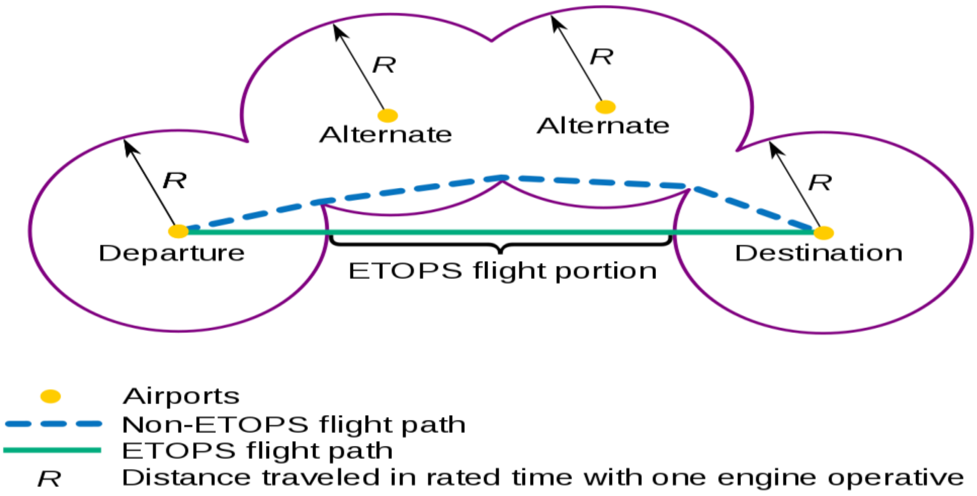


Figure 2 ETOPS schematic illustration [21]

Conclusions

It can be observed that many particular aspects of flights' fuel planning have been considered, many more than the regular flights' operations. It is of importance to notice the attention given by the regulation to wind variations, engine failures and icing hazards. From this, it can be concluded that the regulators consider those operations more prone to fuel-related hazards than the other (less complex) type of operations, such as domestic flights.

The regulations presented in this chapter explicitly state causes of extra fuel burn and, as such, require extra amounts of fuel to be uplifted. The regulator identifies hazards like icing and wind variation to prevent fuel exhaustion events in these flights. Despite that, doubts are unavoidably arising; First of all, the regulator covers only a small amount of the hazards that a flight may face. No explanations have been provided on why only these fuel-related hazards have been covered, if they are considered more important than others, or if they occur more frequently. Additionally, no information has been provided about how the percentages referred in the regulations come up, how the lawmakers were able to provide quantitative rules about the fuel amount needed in the case of appearance of these hazards and if scientific or statistical studies have been performed or if these numbers are arbitrary.

In closing, it would be of importance those percentages to be investigated for their meaningfulness and usefulness, as well as to research if these fuel hazards, namely icing, wind, engine deterioration and APU usage are the most contributing to the overall (unexpected) fuel burn and then, pronounce over the regulation's provisions.

3 Quantitative Safety Risk Assessment (steps 0-3)

In this Chapter, we will demonstrate the first part (steps 0-3) of the quantitative risk assessment performed, towards locating and quantitatively describing risks associated with the identified hazards. Safety risk analysis and assessment constitutes an important part of the Safety Risk Management, which is of utmost importance in the Safety Management System (SMS) framework, as provided by ICAO [22]. Safety Risk Management constitutes a crucial pillar of the SMS, where safety is ensured, by identifying hazards, assessing the risks involved, and by implementing mitigating actions to manage the risks.

There are plenty of methods to perform the risk assessment process [23]**.** To cope with the deficiencies of other models [24]**,** NLR developed a safety risk assessment methodology. This method offers safety risk feedback to advanced air traffic operation design. The safety risk assessment methodology is known as Traffic Organization and Perturbation Analyzer (TOPAZ) [9]. The methodology is mainly based on operational experts' judgement. TOPAZ has been used effectively for safety assessment in a variety of different operations in various sectors, but mainly in the aviation area.

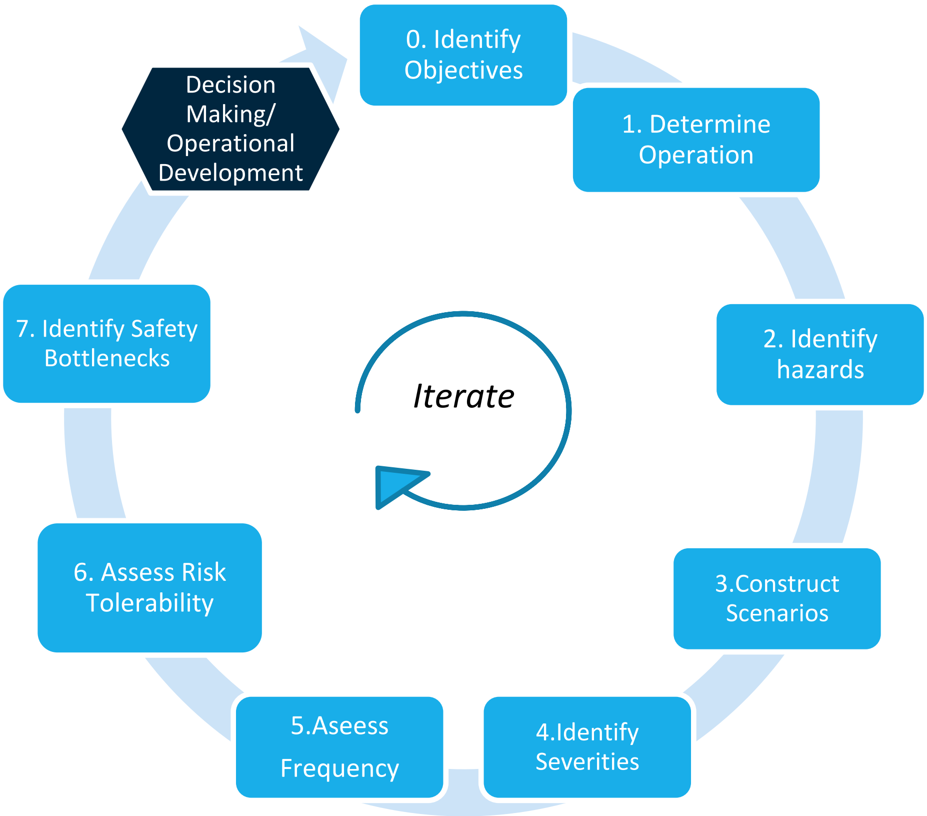


Figure 3 The TOPAZ risk assessment cycle

In TOPAZ methodology, Petri net modelling and Monte Carlo simulation are of utmost importance in modelling and assessment of the air traffic on safety risk. In [25] it is demonstrated how TOPAZ methodology successfully uses Monte Carlo simulation in safety risk assessment of air traffic operation. Prominence is given on how Monte Carlo simulation of safety risk works and the way this is embedded in a comprehensive safety risk assessment cycle.

TOPAZ risk assessment method consists of 8 steps and is of major importance for safety assessing complex systems, like the socio-technical system of aviation operations. Although the cycle itself is in line with the recognized safety risk assessment steps [26], some of these differ essentially. Steps 0 through 5 comprise the safety risk analysis, whilst steps 6 and 7 comprise the comparison of the assessed risk against the acceptability criteria.

In step 0, the assessment's objective, the safety context and the scope are defined. The safety assessment starts by determining the operation that it will go under assessment, at step one. In step two the hazards associated with the operation should be identified, whilst in step three the safety-related scenarios should be constructed. With the employment of the well-established method of the severity and frequency assessment the safety risks associated with each scenario are classified (steps four to six). Monte Carlo simulation plays a very important role in the fifth step (assess frequency).

Finally, for the safety-relevant scenarios with a predicted unacceptable safety risk, the main contributing factors are identified (step seven). Identifying safety bottlenecks will allow us to suggest possible improvements in the design of the operations or regulations. If changes are suggested, a new safety risk assessment cycle should be done (iteration of the TOPAZ cycle) in the direction of investigating the safety risks and assessing any emergent safety issues that may have been introduced.

In the current Chapter, analysis steps 0 through 3 of the TOPAZ methodology are performed and presented. Step 4, as illustrated in Figure 4 below**,** is incorporated in step 0 and substituted by Model Development (presented in the next Chapter). The identification of the objectives is of high importance to better comprehend the analysis' and the assessment's goals. Operations should be clarified in order to define the environment of the analysis, while the hazard identification will render us capable of starting the actual analysis. Finally, the operational scenarios will be developed by using clustered hazards, to facilitate the assessment.

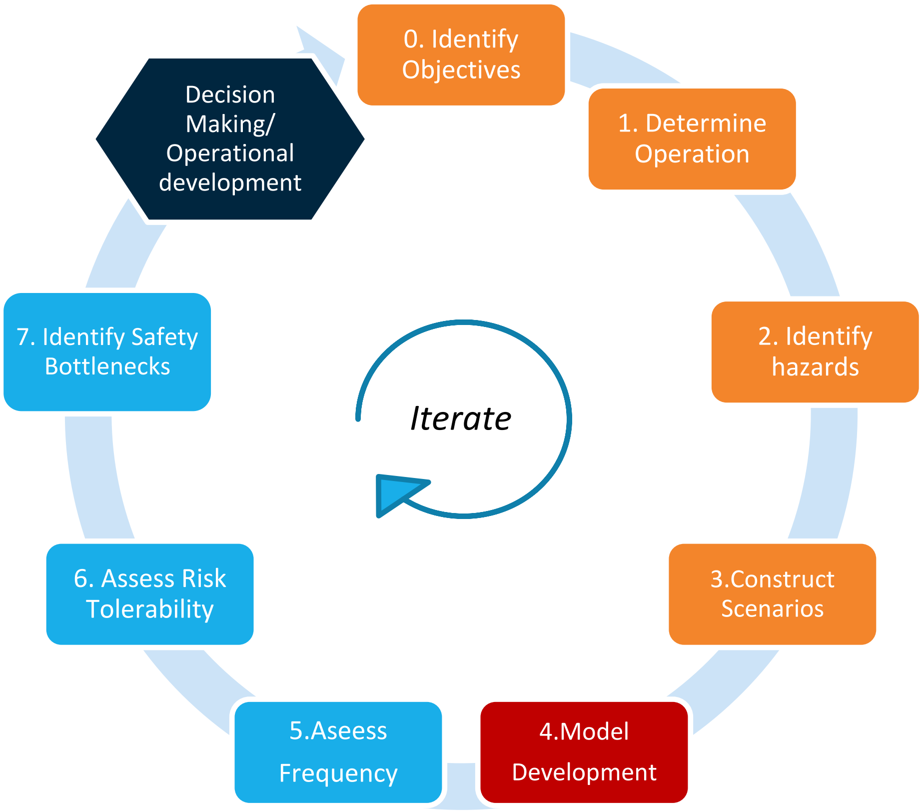


Figure 4 TOPAZ Cycle as modified. The orange-coloured steps are presented in Chapter 3

3.1 Objectives Identification

Prior to commencing the actual safety risk analysis and assessment, the objective and the scope of our study, as well as the level of detail of the assessment should be determined. The study purpose of this analysis is to quantitatively evaluate possible safety risks emerged at the fuel planning and fuel management processes, across the contemporary jet turbine aircraft, in airlines operations (Commercial Air Transport sector).

Objective

The main objective of this safety assessment is to identify and analyse the risks related to fuel planning and fuel management across the airline’s operations. The problem under study is to assess whether the fuel planning criteria, as defined in Chapter 2 and imposed by the regulations for aircraft’s operators, are adequate for the today’s aviation operations, taking into considerations various hazardous factors, such as delays and malfunctions, that may occur in a flight. More specifically, the events “land after using a portion of the FRF” and “fuel exhaustion” will be risk assessed. Finally, the objectives of this study also include the identification of the safety bottlenecks for the developed scenarios.

Scope

The scope of the safety assessment is limited to the risk of fuel unavailability during a flight, thoroughly examining the root causes. Other types of risks, even of more prominence, such as loss of control (LOC) or controlled flight into terrain (CFIT) is out of the scope of this analysis.

Additionally, the safety assessment concerns the examination and analysis of the events described above in both usual and complex flight type operations, only for jet turbine aeroplanes of the commercial air transports (CAT) category. As the usual type of operations, we consider those that are subject to the regulations of section 2.1, concerning the fuel planning criteria. Special (or complex) operations are also considered (ETOPS/EDTO operations), which require special fuel planning treatment. The safety risk assessment that will follow will be of the absolute type, considering all the internal risks of the operations.

Safety context

When defining the safety context of the safety risk assessment, choosing the safety criteria with regard to the safety assessment performed should be defined. Risk assessment of this study aims to be in line with the [22], which provides general directions in the safety risk assessment and management. The quantitative risk assessment methodology employed requires the following features of the risk criteria: a severity classification, a frequency classification and a risk tolerability scheme.

Severity Classification

The determination of the severity of the four described scenarios is dependent on the amount of remaining fuel upon landing (or flight termination), as well as if the landing was performed normally, as described before in the safety context. Therefore, all five severity classes are possible to be realized.

In line with [22], the severity categories are defined as Catastrophic, Hazardous, Major, Minor and Negligible. Despite the general directions ICAO SMM provides, the context of the specific understudy operations should be determined. As presented in the following table, the various severity classes are summarized, whilst also the corresponding context is defined.

Table 3 Severity classification, explanation and context

Value	Severity	Qualitative description (according to ICAO SMM)	Qualitative description (in fuel-related events context)
A	Catastrophic	Equipment destroyed, multiple deaths	Fuel exhaustion while airborne, followed by an unsuccessful emergency landing

B	Hazardous	Large reduction in safety margins, serious injuries, major damages (max 2 fatalities)	Fuel exhaustion while airborne followed by a successful emergency landing
C	Major	Significant reduction in safety margins, serious incident, injury of persons	Landing safely at an airport with very low fuel (less than half the FRF)
D	Minor	Nuisance, operating limitations, use of emergency procedures, minor incident	Landing at an airport with low fuel (between half FRF and FRF)
E	Negligible	Few consequences	Landing at an airport with marginally more fuel than the FRF

Probability Classification

In the quantitative safety assessment methodology, probability (or frequency) classes need to be defined for severity outcomes of conflict scenarios. The severity and frequency classes together are used to define risk tolerability. As there are no specific regulations, directions or safety-related guidance on the definition of the probability categories, we have relative freedom on defining the details of the risk criteria that are required to perform a safety risk assessment, such as maximum acceptable probabilities of accidents or incidents. The frequency terms that will be used in this quantitative safety risk assessment are based on [27]**.** The probability terms, as derived in this section, are shown in Table 4.

Table 4 Probability categories, as described in [22]

Value	Probability category	Meaning	Quantitative description (per flight)
5	Probable (Frequent)	Likely to occur many times	More often than 10^{-3}
4	Occasional	Likely to occur sometimes	Less often than 10^{-3}
3	Remote	Unlikely, but possible to occur	Less often than 10^{-5}
2	Improbable	Very unlikely to occur	Less often than 10^{-7}
1	Extremely improbable	Almost inconceivable that the event will ever occur	Less often than 10^{-9}

Target Level of Safety (TLS)

EU’s vision safety target for the year 2050 is less than one accident per ten million flights [28], which coincides with the safety target of the Advisory Council for Aviation Research and Innovation in Europe (ACARE) [29]. As no TLS has been set formally, for this analysis the TLS is set to the current safety level. So as to define the current safety level (regarding exclusively the fuel-related events), the accident and incident rate is first estimated. Our estimations are demonstrated in the following paragraph.

Current accidents and incidents rate of fuel-related events

In this paragraph, it will be attempted to estimate the current fuel-related accident and incident rate, using disperse information from different formal sources. Estimating those rates is of major importance for our study, as the current rate will be set as the Target Level of Safety. Considering European Aviation Safety Agency reports [30], fuel-related events are rare, in comparison with other accidents and incidents. More specifically, despite fuel-related accidents and incidents were included in the top accidents and incidents categories the latest years, the last safety review by EASA [11] does not include them anymore amongst the prominent accidents' categories, and thus, the category tends to disappear from the top categories. Towards deriving a safety target, especially for the fuel-related events, we need to further investigate the issue. In the following table, we summarize Europe's total accidents and serious incidents rates of the latest years, whilst also the European current accidents/incidents rate.

Table 5 Accidents and serious incidents per million flights (2013-2017) in Europe [11]

Year	Number of accidents or serious incidents per million flights:	Total Current safety rate
2013	14	1.3 accidents or incidents per 10 million flights
2014	13	
2015	11	
2016	15	
2017	13	

In 2016 [31], it was reported that, between 2011 and 2015, there were 30 fuel management occurrences, 9 of them leading to a serious incident, defining as Key Risk Areas for the occurrences (outcomes and precursors) the upset flight, systems failure and terrain conflict. Out of the total reported incidents [31], fuel management category represents only 0.06%, whilst out of the total serious incidents only 3%.

Using data provided in [32] it is concluded that between 1970 and 2010, a total of 30 fuel-related accidents (16 of those were fatal) and 35 fuel-related incidents have occurred worldwide. From the World Data Bank website [33], it is derived that during this period, 626.9 million commercial flights took place. Hence, in this period, we have 0.03 accidents per ten million flights. Summarizing in more detail in Table 6:

Table 6 Current Non-fatal (fatal) accidents and incidents rate

Type of fuel-related event		Number of occurrences (fatal in parenthesis)	Accident rate per 10 million flights (fatal in parenthesis)	Total Number of CAT flights	Period
Total accidents (fatal)	**Total**	**30(16)**	**0.05(0.03)**	**626.9**	**1970-2010**
	Per 10 years period	6(3)	0.06(0.03)	96.8	1970-1979
		4(2)	0.03(0.02)	119.6	1980-1989
		7(5)	0.04(0.03)	173.9	1990-1999
		13(6)	0.05(0.03)	236.6	2000-2009
Incidents	**Total**	**32**	**0.05**	**626.9**	**1970-2010**
	Per 10 years period	0	0	96.8	1970-1979
		1	0.08	119.6	1980-1989
		1	0.06	173.9	1990-1999
		30	0.13	236.6	2000-2010

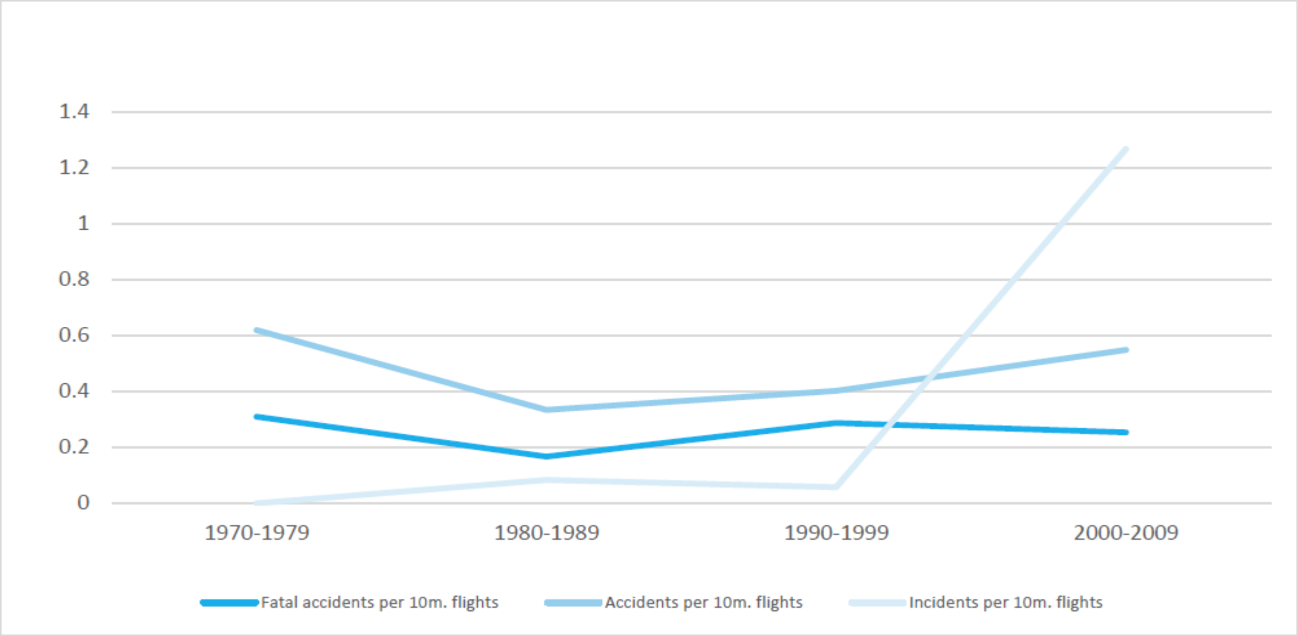


Figure 5 Accidents and incidents rates (per ten million flights)

Commenting on the figure above, it should be first noticed that there is consistency in the accidents rates throughout the last decades, a helpful element for our analysis. The fatal accidents rates are around half of the total accidents, which lie in the area of 0.5 per million flights.

A noticeable fact is that of the incidents rates, which rocketed after 2000. By their nature, incidents may happen but not be identified as easily as accidents, if not reported. A plausible explanation is the dissemination of safety and reporting culture at that period of time, where the aviation safety turned to become more proactive than reactive. As such, we consider the latest incidents rates as more reliable. In closing, setting the safety target at the current safety rates, we calculate:

$$P_{\text{accident}} \leq P_{\text{target}}^{\text{accident}} = 5.0 \cdot 10^{-9}$$

$$P_{\text{incident}} \leq P_{\text{target}}^{\text{incident}} = 1.3 \cdot 10^{-6}$$

Table 7 Summary of Target levels of safety for fuel-related accidents and incidents

Type of fuel-related event	Target Level of Safety (TLS)
Any accident	$5 \cdot 10^{-9}$
Any incident	$1.3 \cdot 10^{-6}$

Risk Tolerability

The risk tolerability assessment is usually performed through the risk tolerability (or acceptability) matrix. Employing this matrix, risks can be classified in accordance with an assessment of their potential severity and frequency for a specific conflict scenario. In this qualitative safety assessment, three risk tolerability classes will be employed: unacceptable, tolerable and negligible.

The risk assessment matrix should be tailored to indicate the context of different operations, to facilitate the assessment. Referring to this matrix, risks may be assessed as unacceptable (red and yellow categories) or acceptable (green categories). The first two categories' risks must be mitigated to reduce their severity and/or frequency. The aircraft operator should consider suspending all those operations which endanger the organization to unacceptable safety risks in the absence of mitigation actions (or while mitigating actions are taken). Below in Table 8, we summarise the three categories of the tolerability matrix.

Table 8 Risk tolerability matrix

Risk index (coloured)		**Description**
🟥	High Significance	Unacceptable under the existing circumstances, meaning that for the specific conflict scenario the risk is above the maximum tolerable probability of an accident or incident.
🟨	Medium Significance	Tolerable based on risk mitigation, meaning that for the involved conflict scenario the risk is below the maximum tolerable probability of an accident or incident.
🟩	Low Significance	Acceptable, meaning that for the conflict scenario the risk below the maximum tolerable probability of an accident or incident and the associated operation would not impose any safety concerns.

Finally, as provided by [22], the various probability categories and the severity classes are analysed in a matrix with values from A to E, regarding the severity and from 1 to 5, regarding the probability. Each element of the matrix is illustrated with a combination of one number and one letter and is also coloured with one of the tolerability matrix colours. This matrix will be later used in the direction of performing the probability /severity risk assessment. In Table 9 we illustrate the described classification.

Table 9 Severity categories

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

Level of detail

This assessment will be of quantitative type. In this type of assessment, quantities will be expressed with numerical values, accompanied by a confidence interval.

Severities identification

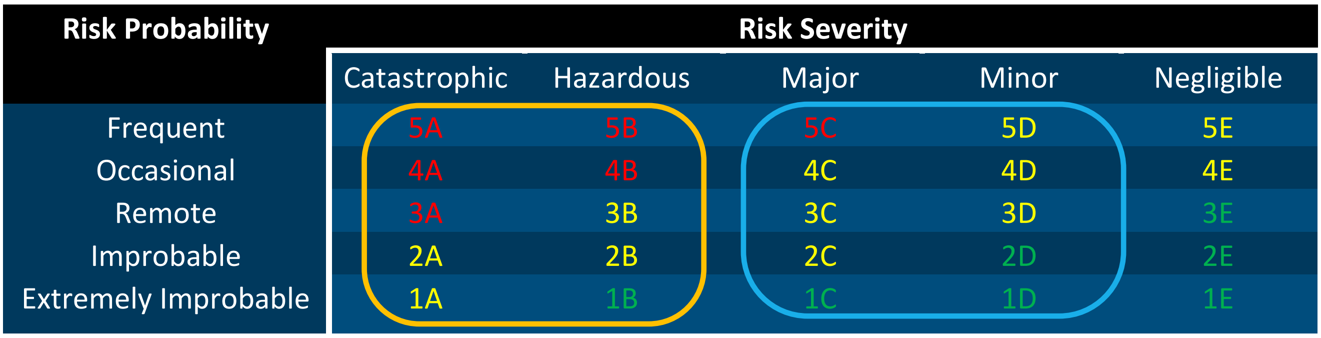
As mentioned in the introduction of the current Chapter, step 4" identify severities" of the TOPAZ methodology is substituted by the step "scenario development", while step 4 is integrated into step 1. So, at this point, we should identify the severities of the events under study. There are two events that we examine. Those are summarized below.

1) An airline jet aeroplane lands after consuming a portion of the Final Reserve Fuel

2) An airline jet aeroplane suffers from fuel exhaustion

Regarding the first event, it is assessed that a safe aeroplane's landing, after consuming a portion of the Final Reserve Fuel, depending on the amount of fuel actually left, it should lie in the severity area of "Major" or "Minor". For the second event it is assessed that an aeroplane suffers fuel exhaustion while flying, depending on the final outcome of the incident/accident, (ranging from successful forced landing with no fatalities to crash landing with several fatalities and total hull loss), lies in the severity area of "Catastrophic" or "Hazardous". Summarizing in Table 10:

Table 10 Event 1 and event 2 severity categories (circled in orange and in blue respectively)



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

3.2 Operations Description

In this section, we will describe the operations that will be examined later in the safety assessment. The objective of the assessment, the operational context, the human roles and responsibilities as well as the intervention of the systems will be discussed.

The operational environment of our quantitative assessment is vague, as we consider the entire flight operations. The identified hazards and inputs come from all flight phases, ranging from pre-flight until after-landing. Within the following sections, the operations will be described, distinguishing different types of flights, governed by different regulations.

Objective

The objective attempts to obtain an indication of how safe the developed operation is. The current Air Operations regulations, as described in Chapter 2, impose specific fuel planning and management rules for different kind of operations. In the previous section 3.1, we have identified quantitative results on the level of safety of the current operations.

Operational context and geographical boundaries

The operational environment of the analysis is the global Commercial Air Transport (CAT) operations, with jet turbine aircraft (passenger and cargo operations), under Instrument Flight Rules (IFR). The operational environment of the developed model is a fraction of the real environment's size-as defined in model specifications Chapter. Special types of operations will be examined, due to their relevance to our subject. The rationale behind this decision is the special fuel regulation which governs these operations, whilst also the special planning requirements and the unavailability of alternate airports. Finally, the geographical boundaries include the entire world operations (airports and airspace).

Human roles and responsibilities

1. Flight crew

Pilot Flying (PF) and Pilot Not-Flying (PNF) is considered as one entity, under the name Flight Crew. Fuel planning is performed by the flight crew, after receiving the airline's dispatch suggestion. The crew makes the final decision concerning the fuel uplift. Fuel management is exclusively performed by the flight crew.

2. Air Traffic Controllers

   Air Traffic Controllers may affect, with their performance and decisions, the progress of the flight. In this analysis, we will not consider each ATC position separately, as it was considered out of the scope. ICAO Annex 11 par. 2.2 states that, amongst others, that the air traffic control services should maintain and expedite an orderly air traffic flow and provide safety information relevant to the flight conduct. As a result, if ATC service is of low quality, flight duration and/or safety could be affected.

3. Airline's Dispatch

   Airline's Dispatch is responsible for planning the flight (route, fuel planning, taking into considerations any special conditions or requirements). Usually, for the fuel planning part of the flight preparation, for which we are mainly concerned, flight dispatchers are using special software to optimise the fuel uplift suggestion to the crew.

4. Ground handlers

   Ground handlers are responsible for handling the aircraft on the apron, including towing, baggage load/unloading, pumping water etc. The most crucial assignment of those, concerning our analysis, is their participation in the fuelling process, as they are responsible for fuelling the aircraft with the amount of fuel ordered (in written) by the Flight's Crew.

Flight types- operational procedures

5. As described in the previous paragraph "Operational context and geographical boundaries".

Technical Systems

6. Aircraft systems

   Flight Systems include the following aircraft's systems: propulsion, FMS, landing gear, APU, anti-ice.

7. ATC systems

   Air Traffic Service radars obtain the aircraft's position and speed.

Services

8. Meteorological service

   Typically, every country provides meteorological information and forecasts to airlines and airports via a meteorological service agency. The forecast is of crucial importance for accurate flight planning and the safe conduct of the flight.

9. NOTAM office service

   NOTAM service provides information on the availability of the airspace.

3.3 Hazards Identification

The objective of the second step of the TOPAZ methodology is to obtain as many hazards as possible, within the scope of the assessment. In safety risk assessment, both wide sense and strict sense hazard definitions are provided. The wide sense approach defines hazards as anything that might have a negative influence, while the strict sense approach describes hazards as a system state or set of conditions that, along with a specific set of worst-case environmental conditions, will eventually lead to an accident [34]. In this research, a hazard is considered as an event (or state) which can lead to a dangerous situation (or may obstruct the resolution of a dangerous situation), usually under certain conditions or in combination with other hazards [35]**.**

As described in [36], Large Aeroplanes accidents and incidents have occurred because of “fuel tank low-level situations or fuel starvation situations, resulting in one or several engine(s) flame out”. The main issues related to fuel planning and fuel management standards, according to the same report, are:

- Technical problems related to Fuel quantity indication.
- Bad weather conditions at the airport of destination combined with flight crew inadequacy or lack of information.
- Trapped fuel situation: adequate fuel quantity is onboard, but part of the fuel amount is unavailable.
- Fuel leaks. When a fuel leak occurs, the risk of total fuel exhaustion is present.
- Insufficient fuel monitoring or management by the pilots. Sometimes this was combined with the preoccupation of the flight crew to communicate aircraft system problems or failures to ATC.
- Erroneous fuel loading, which can lead to low fuel or fuel exhaustion.
- Increased fuel consumption. A situation which if not manages properly and timely may result in fuel exhaustion or fuel low level.

- Navigation errors, which were more frequent in older generation aeroplanes, due to navigation equipment failures or mistakes, resulting in fuel exhaustion.

The initial hazards list

Towards creating a hazard list for our research, we were based on the hazard list developed by [37] and presented in Appendix A. This hazard list first considers the root hazards, which are categorized into three clusters with similar effect or cause. The third cluster is further divided into three sub-clusters as follows:

1. Fuel consumption is higher than expected.
2. The flight route is longer than expected.
3. Part of planned fuel is unavailable.
   a. Fuel lost from tanks due to fuel leakage.
   b. A fraction of fuel in tanks cannot be used by engines.
   c. The fuel intake before the flight was lower than it should, according to the Flight Plan.

Apart from root hazards, hazards not causing fuel-related problems directly are considered; these are called resolution hazards. A subset of the resolution hazards is chosen due to its importance, namely the Situation Awareness. Each hazard is then assigned to one (or more) cluster, and the cluster is divided into sub-clusters based on similar causes of the problem. The following graph shows the method of hazards clustering followed by [37].

The new hazards list

Starting with the aforementioned hazards list as a base, we extended and modified the list. After studying the relevant literature (and performing the respective review), the relevant flight incidents and accidents investigation reports, as well as performing brainstorming sessions with commercial pilots. The newly identified hazards, as well as the hazards included in the initial list of [37], are listed and presented in Appendix B.

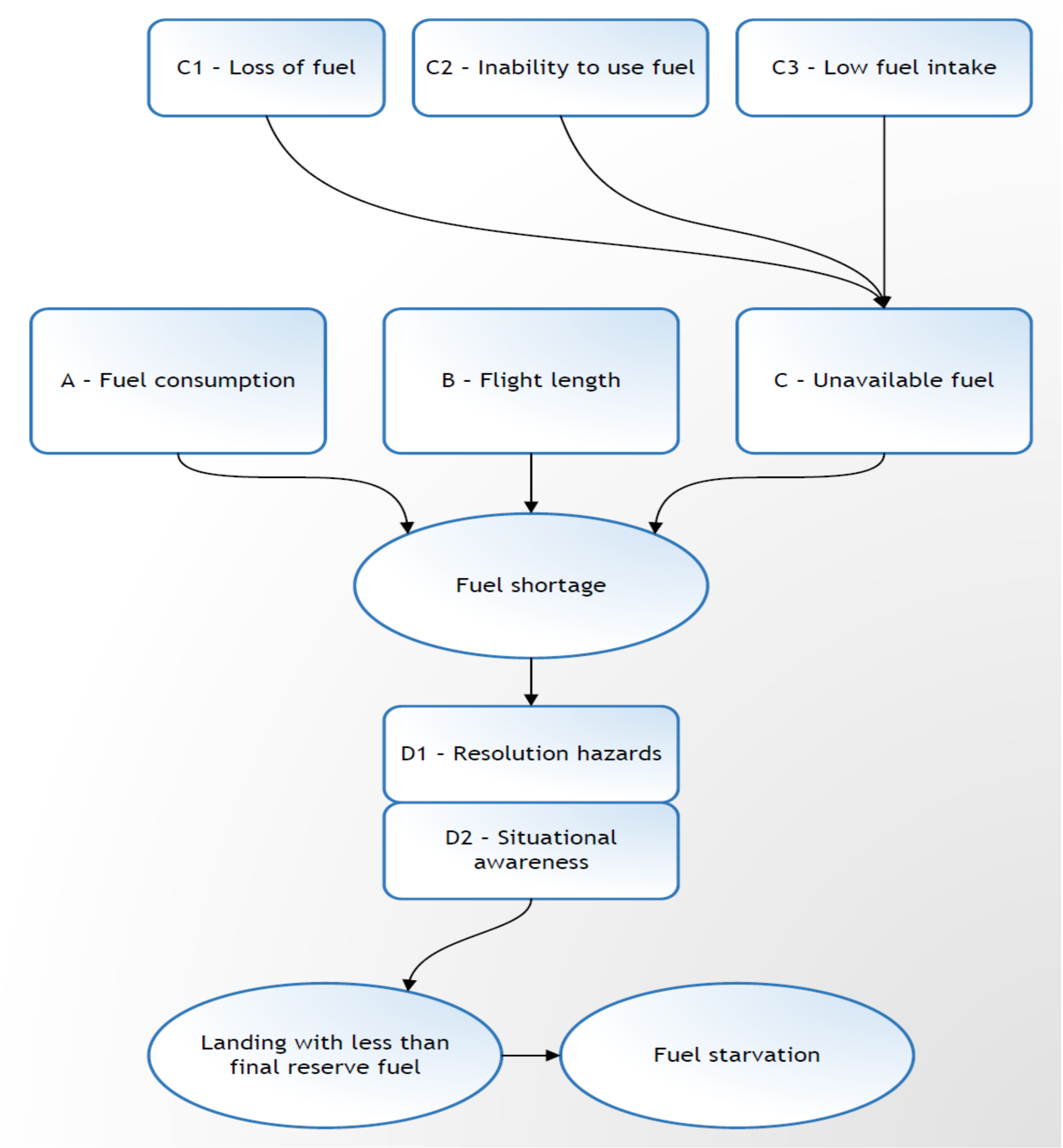


Figure 6 The hazards clustering method followed in [37].

Clustering the new hazards list

Upon the development of the new list of hazards that affect the operations under study, we categorized them into clusters. The clustering method followed is different than the method followed in [37] and described above. In specific, the clustering method followed is two-level: First, we grouped the hazards with respect to their source agent (or non-agent) entity (first level). Second, we further clustered the hazards (second level) with respect to their nature, as presented below in Table 11. For the seven last agents of Table 11, the second level clustering is the same as the first level, due to the small number of hazards of the respective agent.

After further clustering, the hazards of the under-study operations, the (potential) relevant scenarios, which can stem from the identified hazards, should be determined. Each scenario should be used as a compilation or integration point, at which all the applicable hazards are included. Finally, the full list of the clustered hazards is presented in Appendix C.

Table 11 Hazards Clustering (first and second level)

1st clustering level (Agent)	2nd clustering level (hazard's nature)		
Environment	Weather	Airspace and Terrain	Natural phenomena
Airport	Airport weather and natural phenomena	Operational delays and events	Infrastructure
Aircraft	Propulsion and APU	Landing Gear/ Tires	Bleed Air
	CNS	Structure	Fuel System
	FMS and Optimality	Flight Control & Hydraulics	Avionics, Instruments and Electrics
ATCo	Operations	Situation Awareness, human limitations	NOTAM officers
Dispatch	Dispatch	Operations Centre	Policy and Procedures
Flight Crew	Human mistakes	Human Limitations	Experience/ Training/ Culture
ATC System	ATC system		
MRO	MRO		
Cabin Crew	Cabin Crew		
Ground Handling	Ground Handling		
Oversight Authority	Oversight Authority		
Aircraft Manufacturer	Aircraft Manufacturer		
Meteorological Office	Meteorological Office		

3.4 Scenarios Construction

In our analysis, we use all the identified hazards groups in all scenarios. The generic (basic) scenario is an airline's aeroplane, flying from airport O to airport D; the flight may be of a medium, long, or ultra-long length. The difference amongst the scenarios lies in the type of operations: we consider different types of operations that imply a different availability of airports during flight. As alternate airports are of vital importance in airlines operations, the flight crew must always keep open an alternative landing field (to land if the primary destination becomes unavailable). Despite that, there are regulated operations in which pilots may do not have always an alternative option. Lawmakers have published different regulations and different flight planning criteria for such types of operations. This also constitutes an admittance that those types of operations are more hazardous and, hence, of safety interest. In Figure 7 we illustrate the safety-relevant scenario structure, with its central conflict:

***Central conflict**: On-board fuel is not enough to safely land at the destination airport*

All hazards that may lead to the central conflict are grouped into hazard clusters. Each of the identified hazards can be either a root hazard, which can cause a safety-relevant scenario or a resolution hazard, which can complicate the resolution of a safety-relevant scenario. The hazards groups (or clusters) are depicted in 125Appendix C

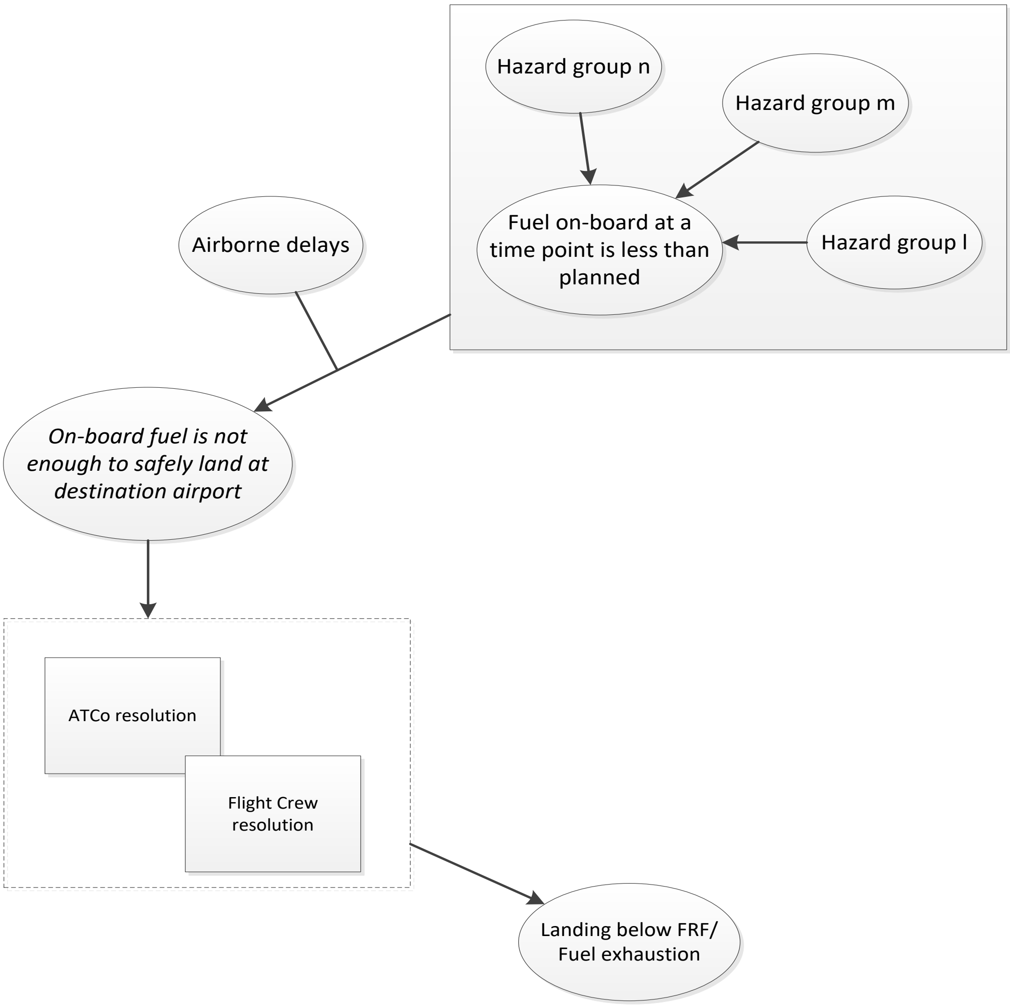


Figure 7 The safety-relevant scenario structure

The scenarios selected to be assessed are described below. The reasoning behind selecting and constructing the below-mentioned scenarios is the following: First, we select the scenario that includes the vast majority of the commercial air transportation; namely, the medium-range flights operated by the two most common aircraft. This scenario represents the most common type of operations with an abundancy of en-route alternate airports; therefore, short diversions to alternate airports may be executed by the aircraft and possibly resolve any fuel shortage. The second scenario was constructed to represent the long-range flights over land. The difference between the first and the second scenario are: the flight length, the alternate airports' availability and the type of aircraft. The reason for constructing this scenario is to identify differences in the safety margins between the medium and long-range flights, given the existence of alternate airports throughout the route. Finally, the last scenario (ETOPS operations) was selected to identify the differences in safety margins between the third and the second scenario, as the operated aircraft types are the same. The main difference between the scenarios is the availability of alternate airports during the cruise phase. Moreover, the third scenario was constructed in the direction of examining the fuel-related ETOPS regulations, as described in the first Chapter. More in detail, the constructed scenarios are illustrated below:

Scenario 1

Continental medium-range flights are considered. The majority of this type of operations worldwide is executed by two aircraft types: Airbus 320 and Boeing 737. Those are the types of aircraft we also consider. This scenario's characteristics are:

1) Normal flight planning regulations (no special requirements).
2) At least 3 airports located in a short distance at any phase of the flight (<200km).

Scenario 2

Long-range flights under the normal flight planning requirements. The aircraft types considered for this type of operations are Airbus 330, Boeing 787 and Airbus 350. This scenario's characteristics are:

1) Normal flight planning regulations (no special requirements).
2) Alternate airports availability during the cruising phase of the flight within a medium distance (<800km)
3) Larger uncertainty of delays and weather forecasts, due to the long flight duration.

Scenario 3

Long-range and ultra-long-range flights under ETOPS fuel planning requirements. The aircraft types considered for this type of operations are Airbus 330 (long-range), Boeing 787 and Airbus 350 (ultra-long-range). This scenario's characteristics are:

1) Special flight planning regulations.
2) Alternate airports unavailability during the cruising phase of the flight (depending on the ETOPS category).
3) Larger uncertainty of delays and weather forecasts, due to the long flight duration.
4) ETOPS categories to be examined: ETOPS240 and ETOPS 370.

4 Safety Risk Model

In this Chapter, we will develop an agent-based dynamic risk model. The objective of this model is to be used in the estimation of the risk probabilities of fuel-related events in airlines operations. The risk model was specified by using the mathematical language of Stochastic Dynamically Coloured Petri Nets (SDCPN) and implemented in JAVA programming language. It should be mentioned that only a high-level description of the model will be presented. A low-level description of the model can be found in Appendix D.

The structure of the current Chapter is as follows: First, a high-level demonstration of the agents and non-agents considered is made, also conducting a Multi-Agent Situation Awareness (MASA) analysis. Situation awareness (SA) describes the perception of environmental elements, their understanding and their projection in the future. MASA captures in a systematic way any differences between SA of all agents. In our analysis, the MASA model includes the SA of all agents as time-dependent information about the SA of all other agents.

Finally, we present some basic elements of the JAVA implementation, the verification and validation processes and the simulation acceleration method employed, along with the problems faced during its implementation.

4.1 Agent-based model description (high-level)

The agents and non-agents considered in the model are the following:

Agents
- Aircraft (AC)
- Airlines Dispatch (AD)
- Flight Crew (FC)
- Flight Management System (FMS)
- Air Traffic Controller (ATCo)
- Cabin Crew (CC)
- Maintenance Repair and Overhaul (MRO)
- Ground Handler (GH)
- Meteorological Service (MET)
- NOTAM Service (NOTAM)
- Air Traffic Control System (ATCS)

Non-agents
- Environment (EN)
- Airport (AP)

In Figure 8 below, we illustrate the high-level relations amongst the agents and non-agents. Agents are illustrated as white circles, while non-agents as white rectangles.

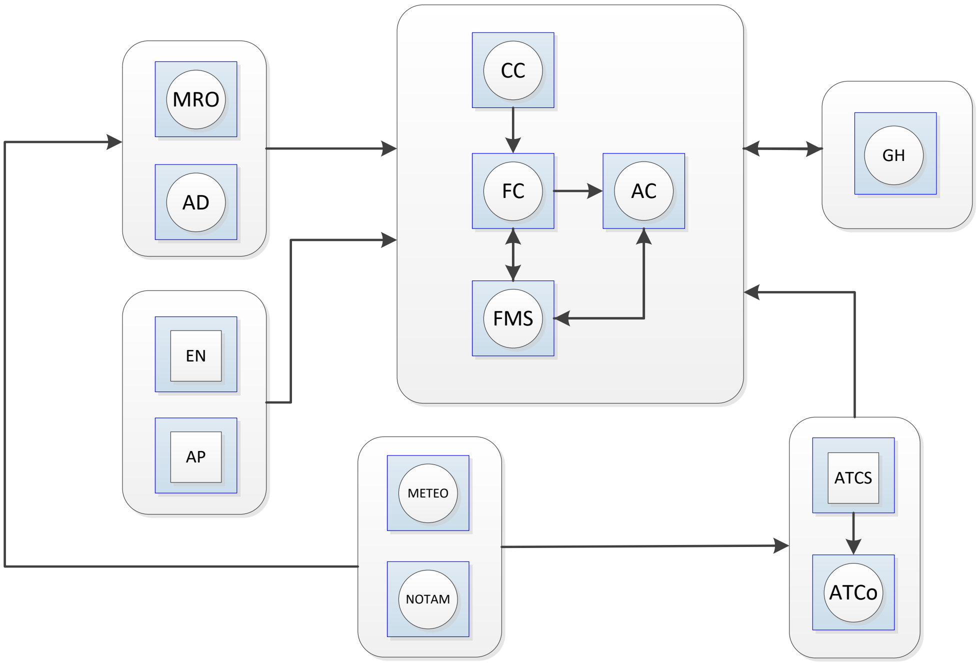


Figure 8 Agents and non-agents relations

Multi-Agent Situation Awareness

As described in [38], an agent is an entity that has Situation Awareness(SA) elements, while a non-agent does not have such elements. A mathematical representation of the SA of agent A for agent B at time t can be expressed as:

$$\sigma_{t,A}^{B} = \begin{pmatrix} i_{t,A}^{B} \\ x_{t,A}^{B} \\ \theta_{t,A}^{B} \\ u_{t,A}^{B} \end{pmatrix}$$

With the following SA components:

- $i_{t,A}^{B}$ denotes the awareness by agent A at time t of the identity of the agent B. (e.g. it can indicate the pilot’s awareness of the identity code of another traffic-aircraft.
- $x_{t,A}^{B}$ denotes the awareness by agent A at time t of the continuous-valued state components of agent B. (e.g. it can indicate the awareness of a ground ATCo of the position of an aircraft.)
- $\theta_{t,A}^{B}$ denotes the awareness by agent A at time t of the discrete-valued state components (modes) of agent B (e.g. it can indicate the awareness of an ATCo of the mode of an alert.)
- $u_{t,A}^{B}$ denotes the awareness by agent A at time t of the intent of agent B. $u_{t,k}$ has various elements, which represent the expectation by agent k at time t of modes and continuous states of

other agents, and related times at which these modes or continuous states are expected to be achieved.

According to the same source [38], SA update is realized by three processes: Observation, Communication, and Reasoning. In each one of the following sections of the current Chapter, a MASA analysis for each agent and non-agent will be performed.

4.1.1 Environment (EN)

4.1.1.1 MASA analysis

Agent's relevant own states

The non-agent entity EN has no SA about itself.

Agent's relevant MASA elements

The non-agent entity EN has no SA about any other agent or non-agent.

4.1.1.2 Assumptions

In our model, we make the following assumptions for the EN SA:

Agent's relevant own states

The non-agent entity EN_j, where j=1 as only one Environment non-agent is considered, at time t, has SA about itself:

$$\sigma_{t,EN_j}^{EN_j} = \begin{pmatrix} Identity_{EN_j}^{EN_j} \\ State_{EN_j}^{EN_j} \\ Mode_{EN_j}^{EN_j} \\ Intent_{EN_j}^{EN_j} \end{pmatrix} = \begin{pmatrix} \text{EN}_j \text{ variables} \\ EN_j \text{ Petri Nets places} \end{pmatrix}$$

Where EN_j variables are:

- sectors' number and dimensions
- airspace hazards
- atmosphere, wind and weather characteristics
- airspace availability
- weather

4.1.1.3 Local Petri Nets

The environment non-agent entity consists of the following LPNs:

- Environment Characteristics (EN_CH)
- Environment Hazards group 1 (EN_HZ_1)

- Environment Hazards group 2 (EN_HZ_2)
- Environment Hazards group 3 (EN_HZ_3)

4.1.1.4 Description

The environment agent includes information about the airspace structure, the atmosphere, the weather and the availability of the airspace.

Airspace structure

The airspace is divided into three types of sectors: small sectors, medium sectors and large sectors, as shown in Figure 9. Each sector (and thus, each part of the environment) has different characteristics. These characteristics concern the weather and availability. All airspace types (small sectors, medium sectors and large sectors) are of square form. Concerning the size relation of the sectors, sectors S_2 and S_3 length equal sector S_1 length multiplied by a factor (specified in the low-level description of the agent).

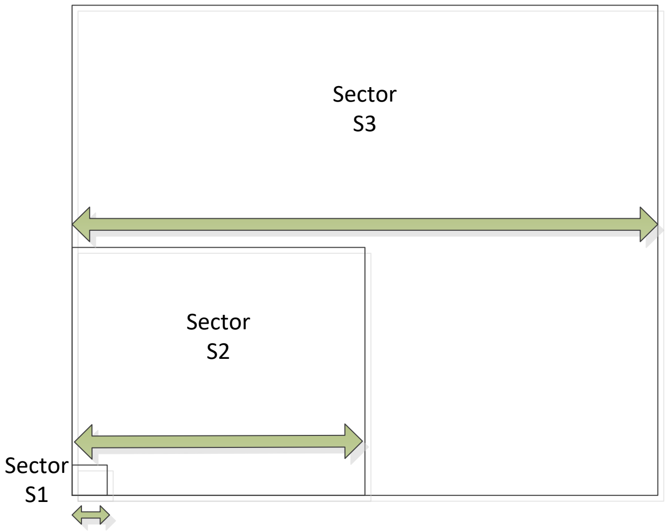


Figure 9 Airspace sectoring

Atmosphere model

The atmosphere model that is used is that of the International Standard Atmosphere (ISA) defined in [39] and also used by [37]. The atmosphere is divided into three layers: the Prandtl layer, Ekman layer and the free atmosphere. In the first two layers, wind speed rises with altitude, while, in the third, wind speed is constant (regarding the altitude). A mathematical presentation of the atmosphere model is demonstrated in the low-level description of the agent.

Weather and wind model

The environment holds the data about the (en-route) weather and wind. Wind and weather characteristics are created in the agent provided to the meteorological service (MET) agent, to create the weather forecast. The mathematical formulas used for the creation of the wind are specified in the low-level description. Due to the contemporary aircraft's airborne equipment (weather radars), weather forecasts and other pilot reports, most of the severe weather phenomena can be avoided. As such, normally aeroplanes do not fly inside severe weather phenomena. Of interest, in our model, are the deviations that can be provoked by weather phenomena and the respective deviation in distance and time of the initial route.

Airspace availability

Airspace is considered available during the flight preparations. During the flight, a part of the airspace may become unavailable, due to the triggering of related hazards. In this case, the Flight Crew will avoid this part of the airspace by deviating, following the Air Traffic Controllers directions.

Environment's hazards group 1, group 2 and group 3

As explained in Chapter 3, hazards' clustering was employed. Hazards group 1 includes the hazards that are related to the airspace closure due to the weather or other natural phenomena. This type of phenomena may provoke airspace closures of sector S_1 type. Hazards groups 2 and 3 include the hazards that are related to the airspace closure due to non-natural phenomena. All groups are specified on the basis of hazards occurrence and airspace size of possible impact (respectively, S_2 sized airspace for group 2 and S_3 for group 3).

4.1.2 Airport (AP)

4.1.2.1 MASA analysis

Agent's relevant own states

The non-agent entity AP has no SA about itself.

Agent's relevant MASA elements

The non-agent entity AP has no SA about any other agent or non-agent.

4.1.2.2 Assumptions

In our model, we make the following assumptions for the AP SA:

Agent's relevant own states

The non-agent entity AP_j, j=1,2,3…N, where N the total number of airports, at time t, has SA about itself:

$$\sigma_{\mathrm{t,AP}_j}^{\mathrm{AP}_j} = \begin{pmatrix} Identity_{AP_j}^{\mathrm{AP}_j} \\ State_{AP_j}^{\mathrm{AP}_j} \\ Mode_{AP_j}^{\mathrm{AP}_j} \\ Intent_{AP_j}^{\mathrm{AP}_j} \end{pmatrix} = \begin{pmatrix} \mathrm{AP}_j \text{ serial number} \\ \mathrm{AP}_j \text{ position} \\ \mathrm{AP}_j \text{ variables} \\ \\ \end{pmatrix}$$

Where AP_j variables are:

- weather condition at the airport
- Taxi time
- Operational hazards at the airport

4.1.2.3 Local Petri Nets

Airport non-agent entity consists of the following LPNs:

- Airports Characteristics (AP_CH)
- Airport Weather (AP_WX)
- Airport Hazards group 1 (AP_HZ_1)
- Airport Hazards group 2 (AP_HZ_2)
- Airport Hazards group 3 (AP_HZ_3)
- Airport Hazards group 4 (AP_HZ_4)
- Airport Hazards group 5 (AP_HZ_5)
- Airport Hazards group 6 (AP_HZ_6)

4.1.2.4 Description

Airport agent carries information about each airport. The information includes the airports' location and taxiing times, airport weather and airport availability or delays.

Airport characteristics

Airport characteristics include the parameters of airports location and taxiing times.

Airport Weather AP_WX LPN

Airport Weather includes information prevailing weather at the airport. Weather at the airports is considered to be of major importance during the flight preparation and fuel planning phase, while also it can be the cause for diversions and long delays. Airport weather hazards are of various types, with different delay impacts. In our model, we have grouped the most menacing weather hazards in five categories, with respect to time of occurring delay. Each airport has separate weather LPN, which includes information about the time of occurrence of weather. The MET agent acquires the airport weather and provides a forecast with a relative error, which is larger for increasing time.

Airport Hazards groups 1-6 LPNs

Several types of delays may occur at an airport, during arrival or departure of a flight. Such delays can be of the following types: ground handling delays, start-up delays, taxing delays, take-off delays, and approach delays. Delays are triggered by various operational hazards, grouped in six major groups. Airport hazards are divided into two phases of flight: departing the airport and approaching the airport. Group 1-4 concern the approach (arriving) phase while groups 5 and 6 concern the departing phase of the flight. Airport hazards groups 5 and 6 (departure) can trigger two situations: Delays at the gate and delays while taxiing. In Table 12 below, the airport operational delays are presented.

Table 12 Airport operational delays groups

Hazards' group name	Event description
AP_HZ_1	ATFM delays during approach (approach)
AP_HZ_2	Runway Unavailable (approach)
AP_HZ_3	Unsafe finals (approach)
AP_HZ_4	Airport unavailable(approach)
AP_HZ_5	Delays during taxing (departure)
AP_HZ_6	Delays at the gate (departure)

4.1.3 Aircraft (AC)

4.1.3.1 MASA analysis

Agent's relevant own states

The agent entity AC_j. j=1,2,3…N, where N the total number of aircraft, at time t, has SA about itself:

$$\sigma_{t,AC_j}^{AC_j} = \begin{pmatrix} Identity_{AC_j}^{AC_j} \\ State_{AC_j}^{AC_j} \\ Mode_{AC_j}^{AC_j} \\ Intent_{AC_j}^{AC_j} \end{pmatrix} = \begin{pmatrix} \text{Callsign} \\ \text{3D Position} \\ \text{flight phase} \\ \end{pmatrix}$$

Agent's relevant MASA elements

Aircraft agent has no MASA for other agents and non-agents

4.1.3.2 Assumptions

In our model, we make the following assumptions for the AC SA:

Agent's relevant own states

The agent entity AC_j, where j=1 as only one aircraft is considered, at time t, has SA about itself:

$$\sigma_{t,AC_j}^{AC_j} = \begin{pmatrix} Identity_{AC_j}^{AC_j} \\ State_{AC_j}^{AC_j} \\ Mode_{AC_j}^{AC_j} \\ Intent_{AC_j}^{AC_j} \end{pmatrix} = \begin{pmatrix} \text{AC variables} \\ \text{Petri Nets places} \end{pmatrix}$$

Where AC variables are:

- 3D position of the aircraft
- Airspeed of the aircraft
- Total fuel consumption
- Amount of fuel left in tanks
- Engines and wing anti-ice system fuel flow
- Landing gear extension system malfunctions.

and Petri Nets place is:

- Ice accumulation on the fuselage.

4.1.3.3 Local Petri Nets

Aircraft agent consists of the following LPNs:

1. Aircraft Characteristics (AC_CH)
2. Aircraft Fuel System (AC_FS)
3. Aircraft Hazards (AC_HZ)
4. Aircraft Icing (AC_IC)
5. Aircraft State (AC_ST)

4.1.3.4 Description

Aircraft agent includes information about the aircraft characteristics, the aircraft systems, the aircraft state and various hazards.

Aircraft Characteristics

Aircraft characteristics include the information concerning the aeroplanes' characteristics and parameters, such as fuel consumption or the various speed values. The information of this LPN is used by the Flight Crew and Airline Dispatch during the planning and by the Flight Crew and the FMS during the flight. The developed model includes a total of five types of aircraft, grouped into three groups with respect to their range: medium-range, long-range and ultra-long-range aircraft, as shown in Table 13 below.

Table 13 Aircraft types considered

Mid-range (<5000km)	Long-range (5.000-12.000km)	Ultra-long range (>12.000km)
Boeing 737-800	Airbus 330-300	Boeing 787-9
Airbus A320-200		Airbus A350-900

Fuel System

The fuel system simulates the rate of fuel consumption for every aircraft, as well as the fuel quantity in the tanks for any given time. Fuel consumption is affected by the thrust level selection for the propulsion source (engines) and by the possible use of the APU or Anti-Ice system usage. Considering the thrust selection as the dependent variable and the ground speed as the independent, fuel consumption for a given aircraft is affected by the wind speed, the flight mode, the altitude, the aircraft's weight, the engines' degradation level and the aerodynamic characteristics of the fuselage (cleanness and potential damages).

The fuel flow consumption model is based on [39]. Finally, pilots can engage systems such as the engines anti-ice or wing anti-ice system to prevent or counteract icing, leading to higher fuel consumption by the engines. Concerning the different flight phases, we may identify six different flight modes: (1) pre-flight (at the gate, not moving, APU is on, engines are off), (2) taxi, (3) climb, (4) cruise, (5) descent and (6) landing.

Aircraft Systems hazards and icing

Aircraft Systems hazards simulate the following aircraft systems: Landing gear, structure, propulsion and anti-ice. Malfunctions of any of these systems can provoke fuel-related problems during the flight, such as fuel leakages or increased consumption. Moreover, aircraft icing may occur on the aircraft's fuselage/engine; in this case, the anti-ice system is activated, incurring additional fuel consumption

Aircraft State

Aircraft state includes the information concerning the three-dimensional position of the aircraft in the environment (x, y coordinates and altitude), as well as the aircraft's current velocity.

4.1.4 Airline's Dispatch (AD)

4.1.4.1 MASA analysis

Agent's relevant own states

The agent entity AD$_{j.}$ j=1,2,3…N, where N the total number of Airlines Dispatch, at time t, has SA about itself:

$$\sigma^{\mathrm{AD}_j}_{\mathrm{t,AD}_j} = \begin{pmatrix} Identity^{\mathrm{AD}_j}_{\mathrm{AD}_j} \\ State^{\mathrm{AD}_j}_{\mathrm{AD}_j} \\ Mode^{\mathrm{AD}_j}_{\mathrm{AD}_j} \\ Intent^{\mathrm{AD}_j}_{\mathrm{AD}_j} \end{pmatrix} = \begin{pmatrix} \text{Airline ID} \\ \\ \\ \end{pmatrix}$$

Agent's relevant MASA elements

The agent entity AD$_j$, j=1,2,3…N, where N the total number of Airlines Dispatch, at time t, has SA about other agents:

About agent MET$_i$, i=1,2,…,N, where N is the total number of Meteorological offices affecting the flight:

$$\sigma_{\mathrm{t,AD}_j}^{MET_i} = \begin{pmatrix} Identity_{\mathrm{AD}_j}^{MET_i} \\ State_{\mathrm{AD}_j}^{MET_i} \\ Mode_{\mathrm{AD}_j}^{MET_i} \\ Intent_{\mathrm{AD}_j}^{MET_i} \end{pmatrix} = \begin{pmatrix} \text{MET ID} \\ \text{MET variables} \\ \\ \\ \end{pmatrix}$$

Where MET variables are:

- current weather information
- weather forecast.

About agent NOTAMi, i=1,2,…,N, where N is the total number of NOTAM offices affecting the flight:

$$\sigma_{\mathrm{t,AD}_j}^{MET_i} = \begin{pmatrix} Identity_{\mathrm{AD}_j}^{MET_i} \\ State_{\mathrm{AD}_j}^{MET_i} \\ Mode_{\mathrm{AD}_j}^{MET_i} \\ Intent_{\mathrm{AD}_j}^{MET_i} \end{pmatrix} = \begin{pmatrix} ID\ \text{NOTAM office} \\ NOTAMs \\ \\ \\ \end{pmatrix}$$

About agent APi, i=1,2,…,N, where N is the total number of airports considered during the flight planning:

$$\sigma_{\mathrm{t,AD}_j}^{\mathrm{AP}_i} = \begin{pmatrix} Identity_{\mathrm{AD}_j}^{\mathrm{AP}_i} \\ State_{\mathrm{AD}_j}^{\mathrm{AP}_i} \\ Mode_{\mathrm{AD}_j}^{\mathrm{AP}_i} \\ Intent_{\mathrm{AD}_j}^{\mathrm{AP}_i} \end{pmatrix} = \begin{pmatrix} \text{Airport ID} \\ \text{Airport characteristics} \\ \\ \\ \end{pmatrix}$$

About agent ACi, i=1,2,…,N, where N is the total number of aircraft operated by the airline:

$$\sigma_{\mathrm{t,AD}_j}^{\mathrm{AC}_i} = \begin{pmatrix} Identity_{\mathrm{AD}_j}^{\mathrm{AC}_i} \\ State_{\mathrm{AD}_j}^{\mathrm{AC}_i} \\ Mode_{\mathrm{AD}_j}^{\mathrm{AC}_i} \\ Intent_{\mathrm{AD}_j}^{\mathrm{AC}_i} \end{pmatrix} = \begin{pmatrix} \text{Aircraft ID} \\ \text{3D position} \\ \\ \\ \end{pmatrix}$$

About agent FCi, i=1,2,…,N, where N is the total number of Pilots employed by the airline:

$$\sigma_{\mathrm{t,AD}_j}^{\mathrm{FC}_i} = \begin{pmatrix} Identity_{\mathrm{AD}_j}^{\mathrm{FC}_i} \\ State_{\mathrm{AD}_j}^{\mathrm{FC}_i} \\ Mode_{\mathrm{AD}_j}^{\mathrm{FC}_i} \\ Intent_{\mathrm{AD}_j}^{\mathrm{FC}_i} \end{pmatrix} = \begin{pmatrix} \text{Crew ID} \\ capability \\ \\ \\ \end{pmatrix}$$

Where capability denotes the pilot’s capability to operate aircraft types and any other restrictions may apply (e.g. flight time limitations)

About agent CC_i, i=1,2,…,N, where N is the total number of Cabin Crew members employed by the airline:

$$\sigma^{\mathrm{CC}_i}_{\mathrm{t,AD}_j} = \begin{pmatrix} Identity^{\mathrm{CC}_i}_{\mathrm{AD}_j} \\ State^{\mathrm{CC}_i}_{\mathrm{AD}_j} \\ Mode^{\mathrm{CC}_i}_{\mathrm{AD}_j} \\ Intent^{\mathrm{CC}_i}_{\mathrm{AD}_j} \end{pmatrix} = \begin{pmatrix} \text{Crew ID} \\ capability \\ \\ \end{pmatrix}$$

Where capability denotes the Cabin Crew member capability to operate aircraft types and any other restrictions may apply (e.g. flight time limitations)

4.1.4.2 Assumptions

In our model, we make the following assumptions for the AD SA:

Agent’s relevant own states

The agent entity AD_j, where j=1 as only one Airline Dispatch is considered, at time t=0 (only at pre-flight phase at t=0 is considered), has no SA about itself.

Agent’s relevant MASA elements

The agent entity AD_j, where j=1 as only one Airline Dispatch is considered, at time t=0 (only at pre-flight phase at t=0 is considered), has SA about other agents as follows:

About the agent AC_i ,i=1,2,3,4,5 , as a total of five aircraft types are considered.

$$\sigma^{\mathrm{AC}_i}_{\mathrm{t,AD}_j} = \begin{pmatrix} Identity^{\mathrm{AC}_i}_{\mathrm{AD}_j} \\ State^{\mathrm{AC}_i}_{\mathrm{AD}_j} \\ Mode^{\mathrm{AC}_i}_{\mathrm{AD}_j} \\ Intent^{\mathrm{AC}_i}_{\mathrm{AD}_j} \end{pmatrix} = \begin{pmatrix} AC \text{ type} \\ AC \text{ characteristics} \\ \\ \end{pmatrix}$$

Aircraft characteristics are:

- Fuel consumption nominal parameters
- Aircraft Aerodynamics parameters

About the agent MET_i, i=1, as only one MET agent is considered

$$\sigma^{MET_i}_{\mathrm{t,AD}_j} = \begin{pmatrix} Identity^{MET_i}_{\mathrm{AD}_j} \\ State^{MET_i}_{\mathrm{AD}_j} \\ Mode^{MET_i}_{\mathrm{AD}_j} \\ Intent^{MET_i}_{\mathrm{AD}_j} \end{pmatrix} = \begin{pmatrix} \text{weather condition} \\ \\ \end{pmatrix}$$

Where whether condition denotes:

- Forecast of the wind speed along x and y-direction

- Forecast of the weather phenomena (en-route).
- Forecast of the airports' weather phenomena

4.1.4.3 Local Petri Nets

AD agent consists of the following LPN:

1. Airline's Dispatch (AD)

4.1.4.4 Description

Airline dispatch agent includes all the flight planning (route planning, fuel planning) information. AD is responsible for making the flight plan, after receiving information about the airports, the en-route weather, the flight's payload and the aircraft types available. Then the dispatch office sends the flight plan to the Flight Crew, including a fuel uplift proposal. AD agent first selects the route to be operated and choose an appropriate, for this route, aircraft. Afterwards, the flight route plan is computed, and the fuel suggestion is estimated. As normally happens, dispatchers consider only the wind during the flight; Later on, the Flight Crew decide for extra fuel due to weather, by using the latest weather forecasts right before the flight. Finally, without loss of generality, the airspace during dispatching is considered available.

4.1.5 Flight Crew (FC)

4.1.5.1 MASA analysis

Agent's relevant own states

The agent entity FC has SA about itself:

$$\sigma_{t,FC_j}^{FC_j} = \begin{pmatrix} Identity_{FC_j}^{FC_j} \\ State_{FC_j}^{FC_j} \\ Mode_{FC_j}^{FC_j} \\ Intent_{FC_j}^{FC_j} \end{pmatrix} = \begin{pmatrix} \text{FC ID} \\ \text{Capability} \\ \\ \end{pmatrix}$$

Where capability denotes the knowledge of which aircraft is the FC member allowed to command.

Agent's relevant MASA elements

The agent entity $FC_{j.}$, j=1,2,3…N, where N the total number of Flight Crew members, at time t, has SA about other agents:

About agent AD_i, i=1,2,…,N, where N is the total number of Airlines' dispatch offices:

$$\sigma_{t,FC_j}^{AD_i} = \begin{pmatrix} Identity_{FC_j}^{AD_i} \\ State_{FC_j}^{AD_i} \\ Mode_{FC_j}^{AD_i} \\ Intent_{FC_j}^{AD_i} \end{pmatrix} = \begin{pmatrix} \text{Dispatch ID} \\ \\ \\ \\ \end{pmatrix}$$

About agent MRO$_i$, i=1,2,…,N, where N is the total number of Maintenance Organizations (MROs):

$$\sigma_{t,FC_j}^{MRO_i} = \begin{pmatrix} Identity_{FC_j}^{MRO_i} \\ State_{FC_j}^{MRO_i} \\ Mode_{FC_j}^{MRO_i} \\ Intent_{FC_j}^{MRO_i} \end{pmatrix} = \begin{pmatrix} \text{MRO ID} \\ \text{MRO notes} \\ \\ \\ \end{pmatrix}$$

Where MRO notes include all aircraft technical notes and information

About agent FMS$_i$, i=1,2,…,N, where N is the total number of aircraft (one FMS per aircraft):

$$\sigma_{t,FC_j}^{FMS_i} = \begin{pmatrix} Identity_{FC_j}^{FMS_i} \\ State_{FC_j}^{FMS_i} \\ Mode_{FC_j}^{FMS_i} \\ Intent_{FC_j}^{FMS_i} \end{pmatrix} = \begin{pmatrix} \text{FMS ID} \\ \text{FMS variables} \\ \\ \\ \end{pmatrix}$$

Where FMS variables are:

- 3D position of the AC
- Relative position to airports
- Fuel consumption
- Aircraft systems information

About agent CC$_i$, i=1,2,…,N, where N is the total number of Cabin Crew members in a specific flight

$$\sigma_{t,FC_j}^{CC_i} = \begin{pmatrix} Identity_{FC_j}^{CC_i} \\ State_{FC_j}^{CC_i} \\ Mode_{FC_j}^{CC_i} \\ Intent_{FC_j}^{CC_i} \end{pmatrix} = \begin{pmatrix} \text{Cabin Crew ID} \\ \text{CC variables} \\ \\ \\ \end{pmatrix}$$

CC variables are:

- cabin state and security
- passengers’ issues
- boarding information

About agent ATCo$_i$, i=1,2,…,N, where N is the total number of ATCo affecting the flight

$$\sigma_{t,FC_j}^{ATCo_i} = \begin{pmatrix} Identity_{FC_j}^{ATCo_i} \\ State_{FC_j}^{ATCo_i} \\ Mode_{FC_j}^{ATCo_i} \\ Intent_{FC_j}^{ATCo_i} \end{pmatrix} = \begin{pmatrix} \\ ATCo \text{ directions} \\ \\ \end{pmatrix}$$

- FC receives directions/clearances from the ATCo

About agent GH$_i$, i=1,2,…,N, where N is the total number of GH affecting the flight

$$\sigma_{t,FC_j}^{GH_i} = \begin{pmatrix} Identity_{FC_j}^{GH_i} \\ State_{FC_j}^{GH_i} \\ Mode_{FC_j}^{GH_i} \\ Intent_{FC_j}^{GH_i} \end{pmatrix} = \begin{pmatrix} \text{Ground Handler ID} \\ \text{Ground Handling state} \\ \\ \\ \end{pmatrix}$$

Ground Handling state denotes if an aircraft GH procedure (refuelling, pushback etc) is completed.

About agent AC$_i$, i=1 (as only one aircraft may be operated by one FC at any time):

$$\sigma_{t,FC_j}^{AC_i} = \begin{pmatrix} Identity_{FC_j}^{AC_i} \\ State_{FC_j}^{AC_i} \\ Mode_{FC_j}^{AC_i} \\ Intent_{FC_j}^{AC_i} \end{pmatrix} = \begin{pmatrix} \text{Aircraft ID} \\ \text{Aircraft variables} \\ \\ \\ \end{pmatrix}$$

Where Aircraft variables are:

- Aircraft flight state
- Aircraft nominal fuel consumption parameters
- Aircraft Aerodynamics characteristics

About agent MET$_i$, i=1,2,…,N, where N is the total number of Meteorological offices affecting the flight

$$\sigma_{t,FC_j}^{MET_i} = \begin{pmatrix} Identity_{FC_j}^{MET_i} \\ State_{FC_j}^{MET_i} \\ Mode_{FC_j}^{MET_i} \\ Intent_{FC_j}^{MET_i} \end{pmatrix} = \begin{pmatrix} \text{MET ID} \\ \text{MET variables} \\ \\ \\ \end{pmatrix}$$

Where MET variables are:

- current weather information
- weather forecast.

About agent NOTAM$_i$, i=1,2,…,N, where N is the total number of NOTAM offices affecting the flight

$$\sigma_{\mathrm{t,FC}_j}^{NOTAM_i}=\begin{pmatrix} Identity_{\mathrm{FC}_j}^{NOTAM_i} \\ State_{\mathrm{FC}_j}^{NOTAM_i} \\ Mode_{\mathrm{FC}_j}^{NOTAM_i} \\ Intent_{\mathrm{FC}_j}^{NOTAM_i} \end{pmatrix}=\begin{pmatrix} ID\ \text{NOTAM office} \\ NOTAMs \\ \\ \end{pmatrix}$$

4.1.5.2 Assumptions

In our model, we make the following assumptions for the FC SA:

Agent's relevant own states

The agent entity FC_j, where j=1 as only one FC is considered, at time t, has no SA about itself.

Agent's relevant MASA elements

The agent entity FC_j, where j=1 as only one FC is considered, at time t, has SA about other agents as follows:

About the agent AD_i, i=1, as only one airline's dispatch is considered.

$$\sigma_{t,FC_j}^{AD_i}=\begin{pmatrix} Identity_{FC_j}^{AD_i} \\ State_{FC_j}^{AD_i} \\ Mode_{FC_j}^{AD_i} \\ Intent_{FC_j}^{AD_i} \end{pmatrix}=\begin{pmatrix} \text{AD ID} \\ \text{AD variables} \\ \\ \end{pmatrix}$$

Where AD variables are

- Final dispatched weight of the aircraft
- Final dispatched fuel
- Flight Plan route

About the agent FMS_i ,i=1 , as only one FMS is considered.

$$\sigma_{t,FC_j}^{FMS_i}=\begin{pmatrix} Identity_{FC_j}^{FMS_i} \\ State_{FC_j}^{FMS_i} \\ Mode_{FC_j}^{FMS_i} \\ Intent_{FC_j}^{FMS_i} \end{pmatrix}=\begin{pmatrix} \text{FMS ID} \\ \text{FMS variables} \\ \\ \end{pmatrix}$$

Where FMS variables are:

- waypoints of the current flight route
- number of waypoints
- planned trip distance
- planned trip time
- index of the destination airport
- index of the alternate airport

- Current amount of fuel in tanks
- amount of fuel needed to get from the current position to the destination airport, to the alternate airport, to the nearest airport and to the second nearest airport
- amount of fuel that the crew computed as the amount needed for known delays at the destination airport, at the alternate airport, at the nearest airport and at the second nearest airport
- current position's sector, altitude, true airspeed, ground speed, vertical speed
- Ongoing aircraft system malfunction

About the agent CC_i ,i=1, as only one CC agent is considered

$$\sigma_{t,FC_j}^{CC_i} = \begin{pmatrix} Identity_{FC_j}^{CC_i} \\ State_{FC_j}^{CC_i} \\ Mode_{FC_j}^{CC_i} \\ Intent_{FC_j}^{CC_i} \end{pmatrix} = \begin{pmatrix} \text{CC ID} \\ \text{CC variables} \\ \\ \end{pmatrix}$$

CC variables are:

- cabin security before take-off and landing

About agent $ATCo_i$, i=1,2,…,N, where N is the total number of ATCo affecting the flight:

$$\sigma_{t,FC_j}^{ATCo_i} = \begin{pmatrix} Identity_{FC_j}^{ATCo_i} \\ State_{FC_j}^{ATCo_i} \\ Mode_{FC_j}^{ATCo_i} \\ Intent_{FC_j}^{ATCo_i} \end{pmatrix} = \begin{pmatrix} ATCo \text{ variables} \end{pmatrix}$$

Where ATCo variables are:

- NOTAM update
- Airport weather update
- Radar vectors instructions, as received from the ATCo Agent.
- ATCo clearance for start-up, taxi-out, take-off, landing

About agent GH_i, where i=1, as only one GH agent is considered:

$$\sigma_{t,FC_j}^{GH_i} = \begin{pmatrix} Identity_{FC_j}^{GH_i} \\ State_{FC_j}^{GH_i} \\ Mode_{FC_j}^{GH_i} \\ Intent_{FC_j}^{GH_i} \end{pmatrix} = \begin{pmatrix} \text{GH variables} \end{pmatrix}$$

Where GH variables are:

- Ground handling procedure state

- Amount of fuel uplifted

About agent AC$_i$, i=1 (as only one aircraft is operated by FC agent at any time):

$$\sigma_{t,FC_j}^{AC_i} = \begin{pmatrix} Identity_{FC_j}^{AC_i} \\ State_{FC_j}^{AC_i} \\ Mode_{FC_j}^{AC_i} \\ Intent_{FC_j}^{AC_i} \end{pmatrix} = \begin{pmatrix} \text{Aircraft ID} \\ \text{Aircraft variables} \\ \\ \end{pmatrix}$$

Where Aircraft variables are:

- Aircraft flight state
- Aircraft nominal fuel consumption parameters
- Aircraft Aerodynamics characteristics

4.1.5.3 Local Petri Nets

Flight Crew agent consists of the following LPNs:

1. Flight Crew Planning (FC_PL)
2. Flight Crew Situation Awareness (FC_SA)
3. Flight Crew Actions (FC_AC)
4. Flight Crew-Flight Evolution (FC_EV)

4.1.5.4 Description

Flight Crew (FC) agent includes the flight planning phase by the FC, the situation awareness of the FC, its actions and its knowledge about the current phase of the flight. The last LPN was considered of major importance, and hence, it was modelled in separate. It should be noted that the FC is considered as a single entity (like having one single pilot) and not as two different entities. Therefore, there is one (common) SA.

Flight Crew Planning

Flight Crew Planning concerns the flight preparations phase. The Flight Crew receives the flight plan (route, aircraft type), the fuel suggestion and the weather forecast from the Airline's Dispatch agent and decides upon extra fuel needs. Flight Crew also receives information about the aircraft's condition from the MRO agent.

Flight Crew Situation Awareness

Situation awareness (SA) is the total of the information, beliefs, and intentions that the Flight Crew has. SA receives information from ATCo, Ground Handlers, FMS, Meteorological Service, Cabin Crew, MRO, Airline, NOTAM office and Aircraft agents.

Flight Crew - Flight Evolution

Flight evolution FC_EV models the Flight's Crew Situation Awareness (SA) about the current phase of the flight. Despite it is part of the Flight Crew SA, it was separated into a different LPN due to its importance. To proceed from any phase of flight to the next one, FC considers the conditions needed, and if the conditions are satisfied, Flight Crew proceeds to the next phase. As there is no related hazard between the SA of the FC about the current phase of the flight and the actual aircraft state (as modelled in Aircraft agent), it is assumed that the Flight Crew's knowledge about the phase of the flights always coincides with the actual phase of the flight.

Flight Crew Actions

Flight Crew Actions FC_AC models any actions that the FC takes. This includes communication with the ATCo and inputs to FMS.

4.1.6 Flight Management System (FMS)

4.1.6.1 MASA analysis

Agent's relevant own states

The agent entity FMS$_i$, i=1,2,3…N, where N the total number of aircraft (as one aircraft has one FMS), at time t, has SA about itself:

$$\sigma_{t,FMS_i}^{FMS_i} = \begin{pmatrix} Identity_{FMS_i}^{FMS_i} \\ State_{FMS_i}^{FMS_i} \\ Mode_{FMS_i}^{FMS_i} \\ Intent_{FMS_i}^{FMS_i} \end{pmatrix} = \begin{pmatrix} \text{FMS ID} \\ \text{FMS variables} \\ \\ \\ \end{pmatrix}$$

Where FMS variables are:

- Navigational Data
- Aircraft parameters

Agent's relevant MASA elements

The agent entity FMS$_j$, j=1,2,3…N, where N the total number of aircraft (as there is one FMS agent per aircraft), at time t, has SA about other agents and non-agents:

About non-agent EN$_i$, i=1:

$$\sigma_{t,FMS_j}^{EN_i} = \begin{pmatrix} Identity_{FMS_j}^{EN_i} \\ State_{FMS_j}^{EN_i} \\ Mode_{FMS_j}^{EN_i} \\ Intent_{FMS_j}^{EN_i} \end{pmatrix} = \begin{pmatrix} \text{wind variables} \\ \\ \\ \end{pmatrix}$$

Where wind variables are:

- wind speed
- wind directions.

About agent $AC_{i,}$, i=1,2,3,…,N, where N the total number of aircraft:

$$\sigma_{t,FMS_j}^{AC_i} = \begin{pmatrix} Identity_{FMS_j}^{AC_i} \\ State_{FMS_j}^{AC_i} \\ Mode_{FMS_j}^{AC_i} \\ Intent_{FMS_j}^{AC_i} \end{pmatrix} = \begin{pmatrix} \text{AC ID} \\ \text{AC variables} \\ \\ \end{pmatrix}$$

Where AC variables are

- Aircraft's current 3D position
- Current fuel flow
- Systems malfunctions

4.1.6.2 Assumptions

In our model, we make the following assumptions for the FMS SA:

Agent's relevant own states

The agent entity FMS_j, where j=1 as only one FMS is considered, at time t, has SA about itself:

$$\sigma_{t,FMS_j}^{FMS_j} = \begin{pmatrix} Identity_{FMS_j}^{FMS_j} \\ State_{FMS_j}^{FMS_j} \\ Mode_{FMS_j}^{FMS_j} \\ Intent_{FMS_j}^{FMS_j} \end{pmatrix} = \begin{pmatrix} FMS \text{ variables} \\ \\ \end{pmatrix}$$

Where FMS variables are:

- Navigational data (waypoints of the flight route, next waypoint, holding fixes)
- planned trip distance and trip time
- destination airport and alternate airport position
- current amount of fuel in tanks
- amount of fuel, distance and time needed to get from current position to destination, alternate airport, nearest airport, second nearest
- amount of fuel that the crew computed as the amount needed for known delays at the destination airport, at the alternate airport, at the nearest airport and at the second nearest airport
- current position's sector, altitude, true airspeed, ground speed, vertical speed

Agent's relevant MASA elements

The agent entity FMS_j, where j=1 as only one FMS is considered, at time t, has SA about other agents/non-agents as follows:

About the non-agent EN$_{i,}$i=1, as only one environment agent is considered:

$$\sigma^{EN_i}_{t,FMS_j} = \begin{pmatrix} Identity^{EN_i}_{FMS_j} \\ State^{EN_i}_{FMS_j} \\ Mode^{EN_i}_{FMS_j} \\ Intent^{EN_i}_{FMS_j} \end{pmatrix} = \begin{pmatrix} \text{wind variables} \\ \\ \\ \end{pmatrix}$$

Where wind variables, at the vicinity of the aircraft, are:

- wind speed
- wind direction

About the agent AC$_{i\,,}$i=1 , as only one aircraft is considered:

$$\sigma^{AC_i}_{t,FMS_j} = \begin{pmatrix} Identity^{AC_i}_{FMS_j} \\ State^{AC_i}_{FMS_j} \\ Mode^{AC_i}_{FMS_j} \\ Intent^{AC_i}_{FMS_j} \end{pmatrix} = \begin{pmatrix} AC\ \text{ID} \\ AC\ \text{variables} \\ \\ \\ \end{pmatrix}$$

Where AC variables are:

- Aircraft’s current 3D position
- Current fuel flow
- Systems malfunctions
- Aircraft nominal fuel consumption parameters
- Aircraft Aerodynamics characteristics
- Aircraft’s true airspeed (TAS)

About the agent AP$_{i\,,}$i=1,2,…,N, where N is the total number of airports

$$\sigma^{AP_i}_{t,FMS_j} = \begin{pmatrix} Identity^{AP_i}_{FMS_j} \\ State^{AP_i}_{FMS_j} \\ Mode^{AP_i}_{FMS_j} \\ Intent^{AP_i}_{FMS_j} \end{pmatrix} = \begin{pmatrix} \text{Airport ID} \\ \text{Airport variables} \\ \\ \\ \end{pmatrix}$$

Where airport variables are:

- Position of all airports
- Taxi times per airport

4.1.6.3 Local Petri Nets

Due to its importance for the conduct of the flight, Flight Management System (FMS) is modelled as a separate agent and not as a part of the aircraft agent. FMS is controlled by the Flight Crew and directly affects the evolution of the flight. The FMS agent comprises of the following LPN:

1. Flight Management System (FMS)

4.1.6.4 Description

Flight Management System acts as an intermediator between the Flight Crew and the Aircraft agents. When the flight crew needs to interact with the aircraft, the information (variables) are provided from FC_SA to FC_AC and then from FC_AC to FMS. This is actually how the aircraft is commanded by the FC. FMS, in addition, provides the Flight Crew with flight-related information, such as the nearest airports and the time left to the destination.

4.1.7 Air Traffic Controller (ATCo)

4.1.7.1 MASA analysis

Agent's relevant own states

The agent entity ATCo$_{i.}$ i=1,2,3…N, where N the total number of ATCos, at time t, has SA about itself:

$$\sigma_{\mathrm{t,ATCo}_j}^{\mathrm{ATCo}_j} = \begin{pmatrix} Identity_{\mathrm{ATCo}_j}^{\mathrm{ATCo}_j} \\ State_{\mathrm{ATCo}_j}^{\mathrm{ATCo}_j} \\ Mode_{\mathrm{ATCo}_j}^{\mathrm{ATCo}_j} \\ Intent_{\mathrm{ATCo}_j}^{\mathrm{ATCo}_j} \end{pmatrix} = \begin{pmatrix} \text{ATCo ID} \\ \text{ATCo position} \\ \\ \\ \end{pmatrix}$$

Where ATCo positions are: ground, taxi, clearance, approach, departure etc.

Agent's relevant MASA elements

The agent entity ATCo$_{i.}$ i=1,2,3…N , where N the total number of ATCos, at time t, has SA about other agents and non-agents:

About the non-agent EN$_{i,}$i=1, as only one environment non-agent is considered:

$$\sigma_{t,ATCo_j}^{EN_i} = \begin{pmatrix} Identity_{ATCo_j}^{EN_i} \\ State_{ATCo_j}^{EN_i} \\ Mode_{ATCo_j}^{EN_i} \\ Intent_{ATCo_j}^{EN_i} \end{pmatrix} = \begin{pmatrix} \text{wind variables} \\ \\ \\ \end{pmatrix}$$

Where wind variables, at the vicinity of the aircraft, are:

- wind speed
- wind direction

About non-agent AP$_i$, i=1,2,…,N, where N is the total number of airports:

$$\sigma_{\mathrm{t,ATCo}_j}^{AP_i}=\begin{pmatrix} Identity_{\mathrm{ATCo}_j}^{AP_i} \\ State_{\mathrm{ATCo}_j}^{AP_i} \\ Mode_{\mathrm{ATCo}_j}^{AP_i} \\ Intent_{\mathrm{ATCo}_j}^{AP_i} \end{pmatrix}=\begin{pmatrix} \text{Airport ID} \\ \text{Airport variables} \\ \\ \end{pmatrix}$$

Where airport variables are:

- Position of all airports
- Taxi times per airport

About agent $AC_{i,}$,i=1,2,3,…,N, where N the total number of aircraft:

$$\sigma_{t,ATCo_j}^{AC_i}=\begin{pmatrix} Identity_{ATCo_j}^{AC_i} \\ State_{ATCo_j}^{AC_i} \\ Mode_{ATCo_j}^{AC_i} \\ Intent_{ATCo_j}^{AC_i} \end{pmatrix}=\begin{pmatrix} \text{AC ID} \\ \text{AC variables} \\ \\ \end{pmatrix}$$

Where AC variables are

- Aircraft’s current 3D position

About agent $FC_{i,}$,i=1,2,3,…,N , where N the total number of FC:

$$\sigma_{t,ATCo_j}^{FC_i}=\begin{pmatrix} Identity_{ATCo_j}^{FC_i} \\ State_{ATCo_j}^{FC_i} \\ Mode_{ATCo_j}^{FC_i} \\ Intent_{ATCo_j}^{FC_i} \end{pmatrix}=\begin{pmatrix} \\ \text{FC variables} \\ \\ \text{FC intentions} \end{pmatrix}$$

Where FC variables and intentions are

- Next waypoint
- Phase of flight
- Change in altitude/speed
- declaration of emergency

About agent MET_i, i=1,2,…,N, where N is the total number of Meteorological offices affecting the ATCo’s sector:

$$\sigma_{t,ATCo_j}^{MET_i}=\begin{pmatrix} Identity_{ATCo_j}^{MET_i} \\ State_{ATCo_j}^{MET_i} \\ Mode_{ATCo_j}^{MET_i} \\ Intent_{ATCo_j}^{MET_i} \end{pmatrix}=\begin{pmatrix} \text{MET ID} \\ \text{MET variables} \\ \\ \end{pmatrix}$$

Where MET variables are:

- current weather information
- weather forecast.

About agent NOTAM$_i$, i=1,2,…,N, where N is the total number of NOTAM offices affecting the ATCo's sector:

$$\sigma_{\mathrm{t,ATCo}_j}^{NOTAM_i} = \begin{pmatrix} Identity_{\mathrm{ATCo}_j}^{NOTAM_i} \\ State_{\mathrm{ATCo}_j}^{NOTAM_i} \\ Mode_{\mathrm{ATCo}_j}^{NOTAM_i} \\ Intent_{\mathrm{ATCo}_j}^{NOTAM_i} \end{pmatrix} = \begin{pmatrix} ID \text{ NOTAM office} \\ NOTAMs \\ \\ \end{pmatrix}$$

About agent ATCS$_i$, i=1,2,…,N, where N is the total number of different ATC system affecting the ATCo's sector:

$$\sigma_{\mathrm{t,ATCo}_j}^{ATCS_i} = \begin{pmatrix} Identity_{\mathrm{ATCo}_j}^{ATCS_i} \\ State_{\mathrm{ATCo}_j}^{ATCS_i} \\ Mode_{\mathrm{ATCo}_j}^{ATCS_i} \\ Intent_{\mathrm{ATCo}_j}^{ATCS_i} \end{pmatrix} = \begin{pmatrix} ATCS \text{ variables} \\ \\ \\ \end{pmatrix}$$

Where ATCS variables are:

- Aircraft 3D position
- Aircraft ground speed
- Aircraft direction

About agent AD$_i$, i=1,2,…,N, where N is the total number of different airlines dispatch offices:

$$\sigma_{\mathrm{t,ATCo}_j}^{AD_i} = \begin{pmatrix} Identity_{\mathrm{ATCo}_j}^{AD_i} \\ State_{\mathrm{ATCo}_j}^{AD_i} \\ Mode_{\mathrm{ATCo}_j}^{AD_i} \\ Intent_{\mathrm{ATCo}_j}^{AD_i} \end{pmatrix} = \begin{pmatrix} \text{Dispatch ID} \\ \text{Flight plan} \\ \\ \end{pmatrix}$$

4.1.7.2 Assumptions

In our model, we make the following assumptions for the ATCo SA:

Agent's relevant own states

The agent entity ATCo$_j$, where j=1 as only one ATCo is considered, at time t, has SA about itself:

$$\sigma_{\mathrm{t,ATCo}_j}^{\mathrm{ATCo}_j} = \begin{pmatrix} Identity_{\mathrm{ATCo}_j}^{\mathrm{ATCo}_j} \\ State_{\mathrm{ATCo}_j}^{\mathrm{ATCo}_j} \\ Mode_{\mathrm{ATCo}_j}^{\mathrm{ATCo}_j} \\ Intent_{\mathrm{ATCo}_j}^{\mathrm{ATCo}_j} \end{pmatrix} = \begin{pmatrix} \text{ATCo ID} \\ \text{ATCo variables} \\ \\ \end{pmatrix}$$

Where ATCo variables are:

- ATCo operational hazards

Agent's relevant MASA elements

The agent entity $ATCo_j$, where j=1 as only one ATCo is considered, at time t, has SA about other agents/non-agents as follows:

About non-agent AP_i, i=1,2,…,N, where N is the total number of airports:

$$\sigma_{t,\mathrm{ATCo}_j}^{AP_i} = \begin{pmatrix} Identity_{\mathrm{ATCo}_j}^{AP_i} \\ State_{\mathrm{ATCo}_j}^{AP_i} \\ Mode_{\mathrm{ATCo}_j}^{AP_i} \\ Intent_{\mathrm{ATCo}_j}^{AP_i} \end{pmatrix} = \begin{pmatrix} \text{Airport ID} \\ \text{Airport variables} \\ \\ \end{pmatrix}$$

Where airport variables are:

- Position of all airports
- Taxi times per airport

About agent MET_i, i=1,2,…,N, where N is the total number of Meteorological offices affecting the ATCo's sector:

$$\sigma_{t,ATCo_j}^{MET_i} = \begin{pmatrix} Identity_{ATCo_j}^{MET_i} \\ State_{ATCo_j}^{MET_i} \\ Mode_{ATCo_j}^{MET_i} \\ Intent_{ATCo_j}^{MET_i} \end{pmatrix} = \begin{pmatrix} \text{MET ID} \\ \text{MET variables} \\ \\ \end{pmatrix}$$

Where MET variables are:

- current weather information

About agent $NOTAM_i$, i=1,2,…,N, where N is the total number of NOTAM offices affecting the ATCo's sector:

- $$\sigma_{t,\mathrm{ATCo}_j}^{NOTAM_i} = \begin{pmatrix} Identity_{\mathrm{ATCo}_j}^{NOTAM_i} \\ State_{\mathrm{ATCo}_j}^{NOTAM_i} \\ Mode_{\mathrm{ATCo}_j}^{NOTAM_i} \\ Intent_{\mathrm{ATCo}_j}^{NOTAM_i} \end{pmatrix} = \begin{pmatrix} ID\ \text{NOTAM office} \\ NOTAMs \\ \\ \end{pmatrix}$$

4.1.7.3 Local Petri Nets

Air Traffic Controller agent consists of the following LPNs:

1. ATCo Situation Awareness (ATCo_SA)
2. ATCo Actions (ATCo_AC)
3. ATCo Hazards group 1 (ATCo_HZ_1)
4. ATCo Hazards group 2 (ATCo_HZ_2)

4.1.7.4 Description

Air Traffic Controller is responsible for the safe and efficient handling of air traffic. In this model, we consider only one type of Air Traffic Controller responsible for the entire airspace and all flight phases. ATCo provides information and route clearances to the Flight Crew, receives information from the Flight Crew (clearance request for every flight phase change and the flight plan), from the NOTAM office (airspace closures) and from the ATC System (the aircraft's position).

ATCo Situation Awareness

ATCo Situation awareness (SA) includes the information, beliefs and intentions that the ATCo has. SA receives information from Flight Crew, ATCo System, Meteorological Service and NOTAM office.

ATCo Actions

ATCo Actions include all the actions the ATCo take. The ATCo take actions based on their SA, giving instructions to the FC agent.

ATCo Hazards groups 1 and 2

There are two simulated hazards group concerning the ATCO agent. Those are the hazards concerning low-efficiency radar vectors and the ATCo not responding (or be absent) during the approach. Both cases introduce additional flight time.

4.1.8 ATC system (ATCS)

4.1.8.1 MASA analysis

Agent's relevant own states

The agent entity ATCS$_{i.}$ i=1,2,3…N, where N the total number of ATCS, at time t, has SA about itself:

$$\sigma_{\mathrm{t,ATCS}_j}^{\mathrm{ATCS}_j} = \begin{pmatrix} Identity_{\mathrm{ATCS}_j}^{\mathrm{ATCS}_j} \\ State_{\mathrm{ATCS}_j}^{\mathrm{ATCS}_j} \\ Mode_{\mathrm{ATCS}_j}^{\mathrm{ATCS}_j} \\ Intent_{\mathrm{ATCS}_j}^{\mathrm{ATCS}_j} \end{pmatrix} = \begin{pmatrix} \text{ATCS ID} \\ ATCS\ \text{state} \\ \\ \\ \end{pmatrix}$$

Where ATCS state denotes if the system is operational

Agent's relevant MASA elements

The agent entity ATCS$_{i.}$ i=1,2,3…N , where N the total number of ATCS, at time t, has SA about other agents and non-agents:

$$\sigma_{\mathrm{t,ATCS}_j}^{\mathrm{AC}_i} = \begin{pmatrix} Identity_{\mathrm{ATCS}_j}^{\mathrm{AC}_i} \\ State_{\mathrm{ATCS}_j}^{\mathrm{AC}_i} \\ Mode_{\mathrm{ATCS}_j}^{\mathrm{AC}_i} \\ Intent_{\mathrm{ATCS}_j}^{\mathrm{AC}_i} \end{pmatrix} = \begin{pmatrix} AC\ \mathrm{ID} \\ AC\ \mathrm{variables} \\ \\ \end{pmatrix}$$

Where AC variables are:

- Aircraft 3D position
- Aircraft groundspeed
- Aircraft direction

4.1.8.2 *Assumptions*

In our model, we make the following assumptions for the ATCS SA:

Agent's relevant own states

The agent entity ATCS$_j$, where j=1 as only one ATCo is considered, at time t, has SA about itself:

$$\sigma_{\mathrm{t,ATCS}_j}^{\mathrm{ATCS}_j} = \begin{pmatrix} Identity_{\mathrm{ATCS}_j}^{\mathrm{ATCS}_j} \\ State_{\mathrm{ATCS}_j}^{\mathrm{ATCS}_j} \\ Mode_{\mathrm{ATCS}_j}^{\mathrm{ATCS}_j} \\ Intent_{\mathrm{ATCS}_j}^{\mathrm{ATCS}_j} \end{pmatrix} = \begin{pmatrix} \mathrm{ATCS\ ID} \\ ATCS\ \mathrm{state} \\ \\ \end{pmatrix}$$

Where ATCS state denotes if the system is operational

Agent's relevant MASA elements

The agent entity ATCS$_j$, where j=1 as only one ATCS is considered, at time t, has SA about other agents as follows:

$$\sigma_{\mathrm{t,ATCS}_j}^{\mathrm{AC}_i} = \begin{pmatrix} Identity_{\mathrm{ATCS}_j}^{\mathrm{AC}_i} \\ State_{\mathrm{ATCS}_j}^{\mathrm{AC}_i} \\ Mode_{\mathrm{ATCS}_j}^{\mathrm{AC}_i} \\ Intent_{\mathrm{ATCS}_j}^{\mathrm{AC}_i} \end{pmatrix} = \begin{pmatrix} AC\ \mathrm{ID} \\ AC\ \mathrm{variables} \\ \\ \end{pmatrix}$$

Where AC variables are:

- Aircraft 3D position
- Aircraft groundspeed
- Aircraft direction

4.1.8.3 Local Petri Nets

ATC systems consist of:

1. Air Traffic Control System (ATCS)

4.1.8.4 Description

ATC system agent comprises the radar, which is a very important technological equipment of the Air Traffic Service. If a malfunction occurs (after a hazard's trigger), the quality of ATCo service will fall, as vectors will not be provided, and procedural ATC will be only available. In this case, the flight time is increased.

4.1.9 Cabin Crew (CC)

4.1.9.1 MASA *analysis*

Agent's relevant own states

The agent entity CC$_{i.}$ i=1,2,3…N, where N the total number of CC, at time t, has SA about itself:

$$\sigma_{t,CC_j}^{CC_j} = \begin{pmatrix} Identity_{CC_j}^{CC_j} \\ State_{CC_j}^{CC_j} \\ Mode_{CC_j}^{CC_j} \\ Intent_{CC_j}^{CC_j} \end{pmatrix} = \begin{pmatrix} \text{CC ID} \\ \text{CC Capability} \\ \\ \\ \end{pmatrix}$$

Where CC Capability is the knowledge of which aircraft allowed to fly with.

Agent's relevant MASA elements

The agent entity CC$_{j.}$ j=1,2,3…N, where N the total number of Cabin Crew members, at time t, has SA about other agents:

About agent AC$_i$, i=1,2,…,N, where N is the total number of aircraft:

$$\sigma_{t,CC_j}^{AC_i} = \begin{pmatrix} Identity_{CC_j}^{AC_i} \\ State_{CC_j}^{AC_i} \\ Mode_{CC_j}^{AC_i} \\ Intent_{CC_j}^{AC_i} \end{pmatrix} = \begin{pmatrix} \text{AC ID} \\ AC\ \text{flight state} \\ \\ \\ \end{pmatrix}$$

About agent FC$_i$, i=1,2,…,N, where N is the total number of Flight Crew members:

$$\sigma_{t,CC_j}^{FC_i} = \begin{pmatrix} Identity_{CC_j}^{FC_i} \\ State_{CC_j}^{FC_i} \\ Mode_{CC_j}^{FC_i} \\ Intent_{CC_j}^{FC_i} \end{pmatrix} = \begin{pmatrix} \text{FC ID} \\ \\ \\ \text{FC intenetions} \end{pmatrix}$$

- FC informs CC about their intentions (takeoff, landing)

4.1.9.2 Assumptions

In our model, we make the following assumptions for the CC SA:

Agent's relevant own states

The agent entity CC_j, where j=1 as only one CC is considered, at time t, has SA about itself:

$$\sigma_{t,CC_j}^{CC_j} = \begin{pmatrix} Identity_{CC_j}^{CC_j} \\ State_{CC_j}^{CC_j} \\ Mode_{CC_j}^{CC_j} \\ Intent_{CC_j}^{CC_j} \end{pmatrix} = \begin{pmatrix} \text{CC ID} \\ CC \text{ Variables} \\ \\ \end{pmatrix}$$

Where CC variables comprise the knowledge of the CC about the cabin security progress (fulfilment of their tasks).

Agent's relevant MASA elements

The agent entity CC_j, where j=1 as only one FC is considered, at time t, has SA about other agents as follows:

About the agent AC_i ,i=1 , as only one aircraft is considered.

$$\sigma_{t,CC_j}^{AC_i} = \begin{pmatrix} Identity_{CC_j}^{AC_i} \\ State_{CC_j}^{AC_i} \\ Mode_{CC_j}^{AC_i} \\ Intent_{CC_j}^{AC_i} \end{pmatrix} = \begin{pmatrix} \text{AC ID} \\ AC \text{ flight state} \\ \\ \end{pmatrix}$$

4.1.9.3 Local Petri Nets

Cabin Crew agent consists of the LPN:

- Cabin Crew (CC)

4.1.9.4 Description

Cabin crew agent provides information to the FC, on whether the cabin is secure or not. A non-safe cabin (for example, unruly passenger or non-finished service) can delay the take-off or landing. An aircraft may take off or land only upon confirmation of the cabin crew that the cabin is secure.

4.1.10 Maintenance Repair and Overhaul (MRO)

4.1.10.1 MASA *analysis*

Agent's relevant own states

The agent entity MRO$_{i.}$ i=1,2,3…N, where N the total number of MRO, at time t, has SA about itself:

$$\sigma_{t,MRO_j}^{MRO_i} = \begin{pmatrix} Identity_{MRO_j}^{MRO_i} \\ State_{MRO_j}^{MRO_i} \\ Mode_{MRO_j}^{MRO_i} \\ Intent_{MRO_j}^{MRO_i} \end{pmatrix} = \begin{pmatrix} \text{MRO ID} \\ \text{MRO variables} \\ \\ \\ \end{pmatrix}$$

Where MRO variables are:

- Maintenance intervals and tasks

Agent's relevant MASA elements

The agent entity MRO$_{i.}$ i=1,2,3…N, where N the total number of MRO, at time t, has SA about other agents:

About agent AC$_i$, i=1,2,…,N, where N is the total number of aircraft of a fleet:

$$\sigma_{t,MRO_j}^{AC_i} = \begin{pmatrix} Identity_{MRO_j}^{AC_i} \\ State_{MRO_j}^{AC_i} \\ Mode_{MRO_j}^{AC_i} \\ Intent_{MRO_j}^{AC_i} \end{pmatrix} = \begin{pmatrix} \text{AC ID} \\ \text{AC variables} \\ \\ \\ \end{pmatrix}$$

Where AC Variables are:

- Aircraft characteristics and parameters

4.1.10.2 Assumptions

Agent's relevant own states

The agent entity MRO$_j$, where j=1 as only one MRO is considered, at time t, has no SA about itself.

Agent's relevant MASA elements

The agent entity MRO$_j$, where j=1 as only one MRO is considered, at time t, has SA about the agent AC$_i$,i=1, as only one aircraft is considered.

$$\sigma_{t,MRO_j}^{AC_i} = \begin{pmatrix} Identity_{MRO_j}^{AC_i} \\ State_{MRO_j}^{AC_i} \\ Mode_{MRO_j}^{AC_i} \\ Intent_{MRO_j}^{AC_i} \end{pmatrix} = \begin{pmatrix} \text{AC ID} \\ \text{AC variables} \\ \\ \\ \end{pmatrix}$$

Where AC variables are:

- Engine condition/identified increased fuel consumption

4.1.10.3 Local Petri Nets

MRO agent consists of the following LPN:

1. Maintenance Repair and Overhaul (MRO)

4.1.10.4 Description

MRO agent is responsible for maintaining the aircraft. MRO agent provides the Flight Crew with information about the aircraft and engines condition (degradation or fuel consumption factor). These factors negatively affect the fuel consumption of the aircraft. MRO agent may provide correctly or not this information to the FC, introducing SA difference between the actual and the expected fuel consumption during flight.

4.1.11 Ground handling (GH)

4.1.11.1 MASA *analysis*

Agent’s relevant own states

The agent entity $GH_{i.}$ i=1,2,3…N, where N the total number of Ground Handlers, at time t, has SA about itself:

$$\sigma^{GH_i}_{t,GH_j} = \begin{pmatrix} Identity^{GH_i}_{GH_j} \\ State^{GH_i}_{GH_j} \\ Mode^{GH_i}_{GH_j} \\ Intent^{GH_i}_{GH_j} \end{pmatrix} = \begin{pmatrix} \text{GH ID} \\ \\ \\ \end{pmatrix}$$

Agent’s relevant MASA elements

The agent entity $GH_{j.}$ j=1,2,3…N, where N the total number of Ground Handlers, at time t, has SA about other agents:

About agent AC_i, i=1,2,…,N, where N is the total number of aircraft:

$$\sigma^{AC_i}_{t,GH_j} = \begin{pmatrix} Identity^{AC_i}_{GH_j} \\ State^{AC_i}_{GH_j} \\ Mode^{AC_i}_{GH_j} \\ Intent^{AC_i}_{GH_j} \end{pmatrix} = \begin{pmatrix} \text{AC ID} \\ \text{AC variables} \\ \\ \end{pmatrix}$$

Where AC variables are:

- Departure/arrival times of aircraft
- Aircraft position

About agent FC_i, i=1,2,…,N, where N is the total number of FC:

$$\sigma^{FC_i}_{t,GH_j} = \begin{pmatrix} Identity^{FC_i}_{GH_j} \\ State^{FC_i}_{GH_j} \\ Mode^{FC_i}_{GH_j} \\ Intent^{FC_i}_{GH_j} \end{pmatrix} = \begin{pmatrix} \text{FC ID} \\ \text{FC variables} \\ \\ \\ \end{pmatrix}$$

Where FC variables are:

- Amount of fuel asked by FC to be uplifted

4.1.11.2 Assumptions

Agent’s relevant own states

The agent entity GH_j, where j=1 as only one GH is considered, at time t, has SA about itself.

$$\sigma^{GH_i}_{t,GH_j} = \begin{pmatrix} Identity^{GH_i}_{GH_j} \\ State^{GH_i}_{GH_j} \\ Mode^{GH_i}_{GH_j} \\ Intent^{GH_i}_{GH_j} \end{pmatrix} = \begin{pmatrix} \text{GH ID} \\ \text{GH variables} \\ \\ \\ \end{pmatrix}$$

Where GH variables are:

- Fuelling progress
- GH progress (completion)

Where MRO variables are the colour variables of the MRO agent, as defined in Appendix D.12.

Agent’s relevant MASA elements

The agent entity GH_j, where j=1 as only one GH is considered, at time t, has SA about other agents as follows:

About agent AC_i, i=1, as only one aircraft is considered:

$$\sigma^{AC_i}_{t,GH_j} = \begin{pmatrix} Identity^{AC_i}_{GH_j} \\ State^{AC_i}_{GH_j} \\ Mode^{AC_i}_{GH_j} \\ Intent^{AC_i}_{GH_j} \end{pmatrix} = \begin{pmatrix} \text{AC ID} \\ AC \text{ flight state} \\ \\ \\ \end{pmatrix}$$

About agent FC_i, i=1, as only one FC agent is considered:

$$\sigma^{FC_i}_{t,GH_j} = \begin{pmatrix} Identity^{FC_i}_{GH_j} \\ State^{FC_i}_{GH_j} \\ Mode^{FC_i}_{GH_j} \\ Intent^{FC_i}_{GH_j} \end{pmatrix} = \begin{pmatrix} \text{FC ID} \\ FC \text{ variables} \\ \\ \\ \end{pmatrix}$$

Where FC variables are:

- The amount of fuel asked to be uplifted

4.1.11.3 Local Petri Nets

Ground handling agent consists of one LPN:

1. Ground Handling (GH)

4.1.11.4 Description

Ground Handling is responsible for providing the following ground services to the aircraft: refuelling and handling. The Ground Handling agent receives information about fuel uplift quantity by the Flight Crew, as well as pushback the aircraft. The GH hazards considered include mistakes in the refuelling quantity and delays in the towing procedure.

4.1.12 Meteorological Service (MET)

4.1.12.1 MASA *analysis*

Agent's relevant own states

The agent entity $MET_{i.}$ $i=1,2,3 \ldots N$, where N the total number of Meteo service offices, at time t, has SA about itself:

$$\sigma_{t,MET_j}^{MET_i} = \begin{pmatrix} Identity_{MET_j}^{MET_i} \\ State_{MET_j}^{MET_i} \\ Mode_{MET_j}^{MET_i} \\ Intent_{MET_j}^{MET_i} \end{pmatrix} = \begin{pmatrix} \text{MET variables} \\ \\ \\ \end{pmatrix}$$

Agent's relevant MASA elements

The agent entity $MET_{j.}$ $j=1,2,3 \ldots N$, where N the total number of Meteo service offices, at time t, has SA about other agents:

About agent EN_i, i=1, as only one Environment may be considered

$$\sigma_{t,MET_j}^{EN_i} = \begin{pmatrix} Identity_{MET_j}^{EN_i} \\ State_{MET_j}^{EN_i} \\ Mode_{MET_j}^{EN_i} \\ Intent_{MET_j}^{EN_i} \end{pmatrix} = \begin{pmatrix} EN \text{ variables} \\ \\ \\ \end{pmatrix}$$

Where EN variables are:

- Weather phenomena
- Weather parameters
- Weather forecast

4.1.12.2 Assumptions

In our model, we make the following assumptions for the MET SA:

Agent's relevant own states

The agent entity MET_j, where j=1 as only one MET is considered, at time t, has no SA about itself.

Agent's relevant MASA elements

The agent entity MET_j, where j=1 as only one MET is considered, at time t, has SA about other agents as follows:

About the agent EN_i, i=1 , as only one EN (non)agent is considered:

$$\sigma_{t,MET_j}^{EN_i} = \begin{pmatrix} Identity_{MET_j}^{EN_i} \\ State_{MET_j}^{EN_i} \\ Mode_{MET_j}^{EN_i} \\ Intent_{MET_j}^{EN_i} \end{pmatrix} = \begin{pmatrix} EN\ \text{variables} \\ \\ \\ \end{pmatrix}$$

Where EN variables are:

- Wind direction and speed per altitude
- Weather at airports
- Weather and wind forecast

About the agent AP_i, i=1,2,..,N at time t:

$$\sigma_{t,MET_j}^{AP_i} = \begin{pmatrix} Identity_{MET_j}^{AP_i} \\ State_{MET_j}^{AP_i} \\ Mode_{MET_j}^{AP_i} \\ Intent_{MET_j}^{AP_i} \end{pmatrix} = \begin{pmatrix} \text{AP variables} \\ \\ \\ \end{pmatrix}$$

Where AP variables are:

- Weather at Airports
- Weather forecast for Airports

4.1.12.3 Local Petri Nets

Meteorological Service Agent consists of the LPN:

1. Meteorological Service (MET)

4.1.12.4 Description

This agent is responsible for providing the weather forecast to the Flight Crew and the Dispatch office before and during the flight. To do so, MET agent receives information for the Environment and Airport weather agents about the current and future weather. By using this information, MET agent creates the weather forecast, which is governed by a time-dependent error which increases with time. As the forecast error becomes larger for longer forecasts, is more significant for long-range flights. Met service updates its weather information every 30 minutes.

4.1.13 NOTAM Office (NOTAM)

4.1.13.1 MASA *analysis*

Agent's relevant own states

The agent entity NOTAM$_{i.}$ i=1,2,3…N, where N the total number of NOTAM offices, at time t, has SA about itself:

$$\sigma_{t,NOTAM_i}^{NOTAM_i} = \begin{pmatrix} Identity_{NOTAM_i}^{NOTAM_i} \\ State_{NOTAM_i}^{NOTAM_i} \\ Mode_{NOTAM_i}^{NOTAM_i} \\ Intent_{NOTAM_i}^{NOTAM_i} \end{pmatrix} = \begin{pmatrix} NOTAM\ \ ID \\ \\ \\ \end{pmatrix}$$

Agent's relevant MASA elements

The agent entity NOTAM$_{j.}$ j=1,2,3…N, where N the total number of NOTAM offices, at time t, has SA:

About the agent AP$_{i}$,i=1,2,..,N at time t:

$$\sigma_{t,NOTAM_j}^{AP_i} = \begin{pmatrix} Identity_{NOTAM_j}^{AP_i} \\ State_{NOTAM_j}^{AP_i} \\ Mode_{NOTAM_j}^{AP_i} \\ Intent_{NOTAM_j}^{AP_i} \end{pmatrix} = \begin{pmatrix} AP\ \text{variables} \\ \\ \\ \end{pmatrix}$$

Where AP variables are:

- Airport information related to flight safety

About the agent EN$_{j}$,j=1, at time t:

$$\sigma_{t,NOTAM_j}^{EN_i} = \begin{pmatrix} Identity_{NOTAM_j}^{EN_i} \\ State_{NOTAM_j}^{EN_i} \\ Mode_{NOTAM_j}^{EN_i} \\ Intent_{NOTAM_j}^{EN_i} \end{pmatrix} = \begin{pmatrix} \text{EN variables} \\ \\ \\ \end{pmatrix}$$

Where EN variables are:

- Natural phenomena or events that affect flight safety (e.g. Volcanos)

4.1.13.2 Assumptions

Agent's relevant own states

The agent entity NOTAM$_j$, where j=1 as only one NOTAM is considered, at time t, has no SA about itself.

Agent’s relevant MASA elements

The agent entity NOTAM$_j$, where j=1 as only one NOTAM is considered, at time t, has SA about other agents as follows:

About the agent EN$_j$,j=1, as only one Environment non-agent is considered, at time t:

$$\sigma_{t,NOTAM_j}^{EN_i} = \begin{pmatrix} Identity_{NOTAM_j}^{EN_i} \\ State_{NOTAM_j}^{EN_i} \\ Mode_{NOTAM_j}^{EN_i} \\ Intent_{NOTAM_j}^{EN_i} \end{pmatrix} = \begin{pmatrix} \text{EN variables} \\ \\ \\ \end{pmatrix}$$

Where EN variables are:

- Airspace availability

4.1.13.3 Local Petri Nets

NOTAM Office agent consists of the LPN:

1. NOTAM office (NOTAM)

4.1.13.4 Description

The NOTAM agent provides information about airspace restrictions to the ATCo during the flight. NOTAM information is being updated every 30min. It is also assumed that when a NOTAM sets a sector as unavailable, the entire airspace (vertically) becomes unavailable.

4.2 Model implementation

In this section, we will demonstrate some fundamental details of the implementation of the developed risk model. Moreover, some verification and validation examples will be shown, as part of the respective processes took place after the implementation. Finally, the simulation acceleration method chosen and implemented will be thoroughly demonstrated, as well as its validation process.

4.2.1 Structure of the Java program

After designing and verifying the Petri net model of the previous Chapter, we implemented it in Java. The reasons of choosing JAVA as the programming language of the implementation is twofold: First and foremost, because the work of [37], which served as a basis for this thesis project, was implemented also in Java. Second, because Java is a contemporary, object-oriented and rich in libraries languages, which is appropriate for implementing agent-based modelling. Indeed, object-oriented languages are a useful tool for implementing agent-based models, as each agent can be implemented as an object (or cluster of objects). Finally, some fundamental parts of the program structure will be presented.

After the implementation and the debugging of the code, we were able to produce our first results and continue with the verification and validation of the algorithm, as well as to perform a sensitivity analysis. Finally, a major issue which was expected to be faced and it finally arose, was that of the computational time. Straight-forward (also named as regular or crude) Monte Carlo simulation is not efficient when dealing with rare events. Despite the fact that it was achieved to reduce the computational time per flight in comparison with [37] significantly, still some acceleration simulation techniques should be performed. The Monte Carlo Splitting Method designed and implemented in [37] was not applicable to our work due to reasons that will be discussed later. Hence, other methods (or the same but by designing it from scratch) should be identified.

The basic structure characteristic of our implementation is that each LPN of the Petri net model is implemented as a separate java class. The various agent classes are using the parent class *LocalPetriNet*, in which various methods and functions are saved and used by all agents (for example, the various distributions).

Table 14 The classes of the program. Each class represents one LPN

AC_CH	AP_CH	ATCO_SA	MRO
AC_FS	AP_WX	ATCO_AC	FC_PL
AC_HZ	AP_HZ_1	ATCS	FC_SA
AC_IC	AP_HZ_2	ATCO_HZ_1	FC_EV
AC_ST	AP_HZ_3	ATCO_HZ_2	FC_AC
AD	AP_HZ_4	EN_CH	GH
CC	AP_HZ_5	EN_HZ_1	
FMS	AP_HZ_6	EN_HZ_2	
MET	NOTAM	EN_HZ_3	

Within the class, the parameters and colour variables are of private type. Initial markings, colour functions and transitions are public methods. All objects of the classes are then used all together to run one simulation which is actually one flight. All the classes of the table above are called by the class SimulationMCR, which is finally called by the class MonteCarloRegular. In this final class, all the Monte Carlo parameters may be found. Upon the end of each flight's simulation, all the variables are saved in objects of the class Results.

As it will be explained later, an acceleration simulation technique -called IPS- was also implemented. In this case, the class that governs the simulation is SimulationIPS, which is run by the class MonteCarloIPS. Finally, in objects of the class Levels are saved the all the variables values needed for the run of the IPS algorithm. At the end of the MonteCarlo simulation, one file with all the variables of each flight is printed.

Table 15 The classes of the program related to the Monte Carlo simulation

MonteCarloRegular	SimulationMCR
MonteCarloIPS	SimulationIPS
Results	Levels

4.2.2 Verification

Verification involves the simulation code being debugged to ensure it works correctly, in accordance with the specified model. The verification process of the simulation code was performed for all agents and non-agent entities included, ensuring that the code works as specified in the SDCPN model. In this section, we will demonstrate some examples of how the verification was performed for some model's agents. Despite we verified the entire model through various ways, such as graphs and variables values monitoring while the program was running in debugging mode, due to the large number of agents, non-agents and variable, we will only demonstrate some examples.

After the implementation of the code in Java, test flights were created to check and compare the basic flight variables. This constitutes the first but fundamental verification test of the algorithm. After gathering data from various random flights, the corresponding plots were created and illustrated below. The important variables that the plots demonstrate are speed, time and position (three dimensions). The following Figure 10 and Figure 11 illustrate the two-dimensional position (x, y) and the three-dimensional position for the same flight.

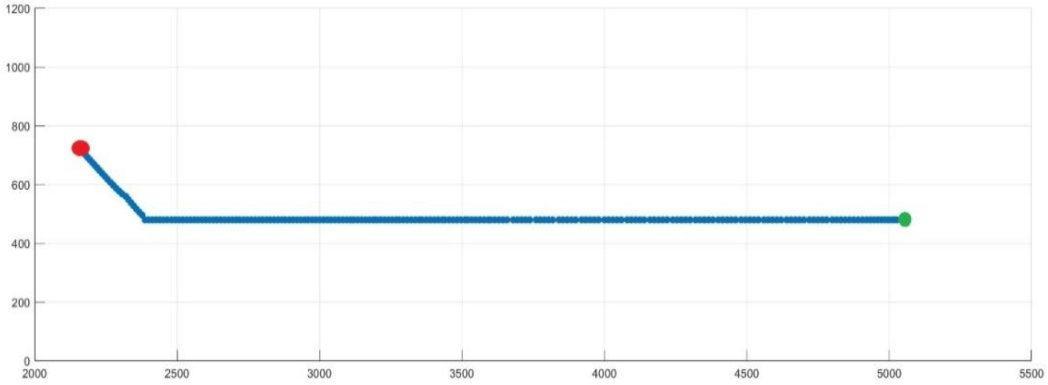


Figure 10 2-D graph plot of a flight. The axes dimensions are in km.

From the figure above it can be seen that the aeroplane takes off from the red spot and lands at the green spot, following a route of approximately 3000 km.

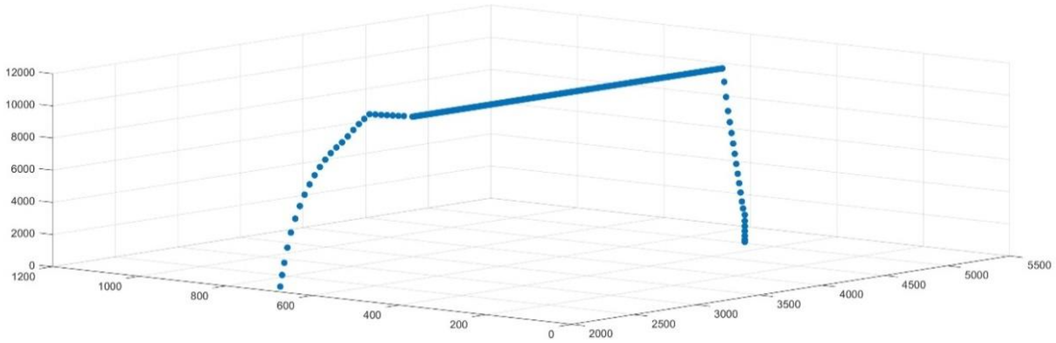


Figure 11 3-D plot of a flight. Horizontal axes are in km, the vertical in m.

In Figure 11 we may see the climb, cruise and descent phase of the specific flight. Using such graphs, we verified the correctness of the flight path. Through this kind of plots, we verified various agents, such as FMS, FC_AC and AD. Using flight data as in the verification part, we created plots of the altitude, time and groundspeed. In Figure 12 we illustrate all three variables in the same time plot. We may verify that the altitude during the cruise is constant while ground speed fluctuates due to wind, again during the cruise phase. This graph will be also used later in the validation.

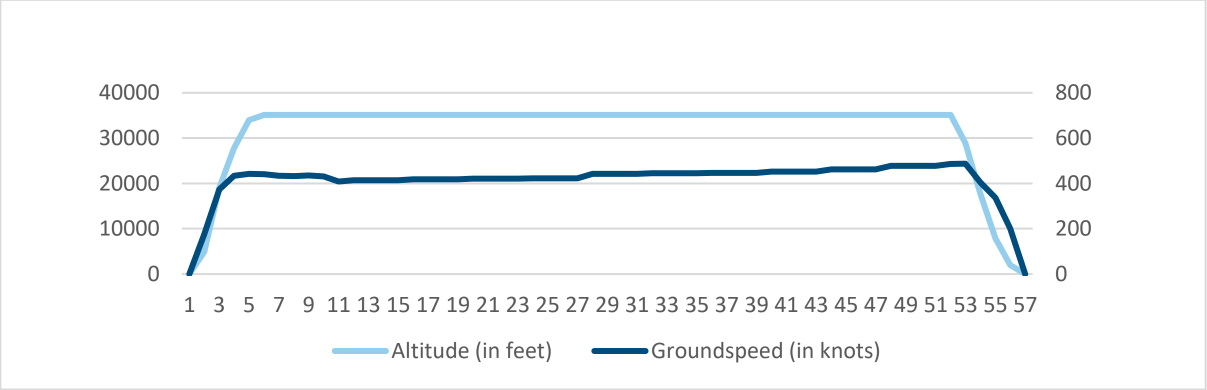


Figure 12 Altitude-Groundspeed vs time (time in 5min periods)

Concerning the Airlines Dispatch (AD) agent verification, we also illustrate some important variables of the agent. In particular, AD calculates and makes recommendations to the FC_PL (Flight Crew Planning) about the amount of fuel to be uplifted, according to the regulations. Figure 13 illustrates the amount of fuel calculated for 200.000 flights for Boeing 737-800 aircraft, for several different flights, between 30 airports in total. We see, as we expected, that the amount of fuel uplift for taxi lies in the area of 70-270 kg, whilst in most cases is between 100 and 150kg. This value depends on the airport mean taxiing time, as specified in model non-agent Airport (AP).

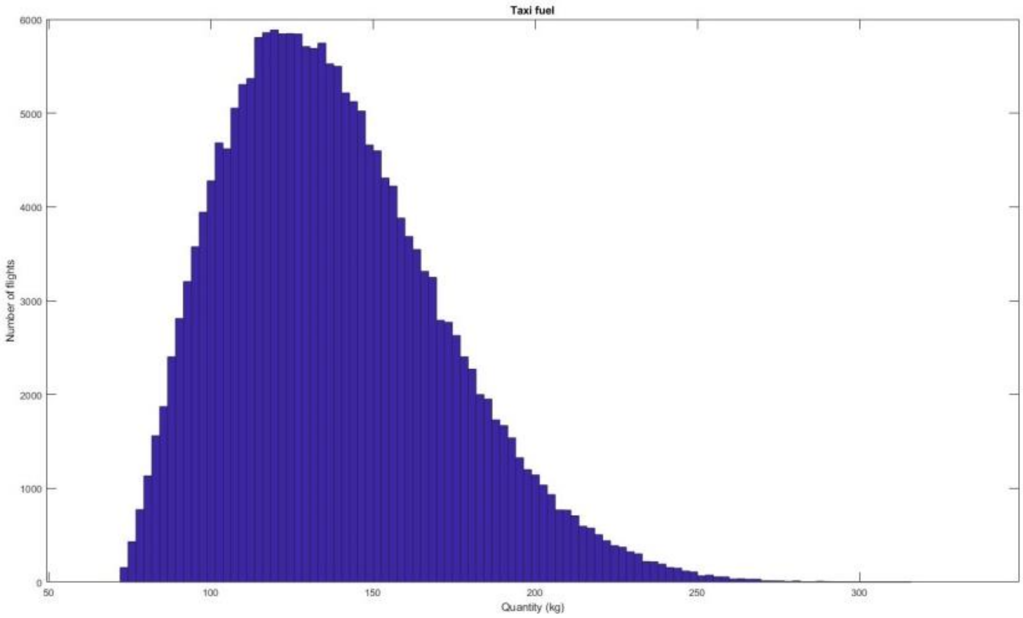


Figure 13 Taxi fuel uplifted for 200.000 flights (Boeing 737-800)

One more example for the same agent is the amount of Trip, Contingency and Final Reserve fuel. Figure 14 illustrates the values of those three variables (3000 runs), for Airbus 320 flights of a specific route. It can be excluded that for all flight the trip fuel is around 10000kg, fluctuating around 300kg. Despite the graph comes from the exact same aircraft type and O-D (origin-destination) pair, the fluctuation seen was expected; this is because trip fuel includes the fuel calculated for the wind, verifying simultaneously part of the environment non-agent entity.

Concerning the contingency fuel, as the specific flight illustrated is relatively long for medium-range flights (around 4h flight time), the contingency fuel is determined as 5% of the trip fuel. Indeed we can see that with small fluctuations due to the trip fuel variable respective behaviour, the amount of contingency fuel is around 500kg. Finally, the FRF amount is around 900kg, fluctuating due to the payload mass of the specific flight.

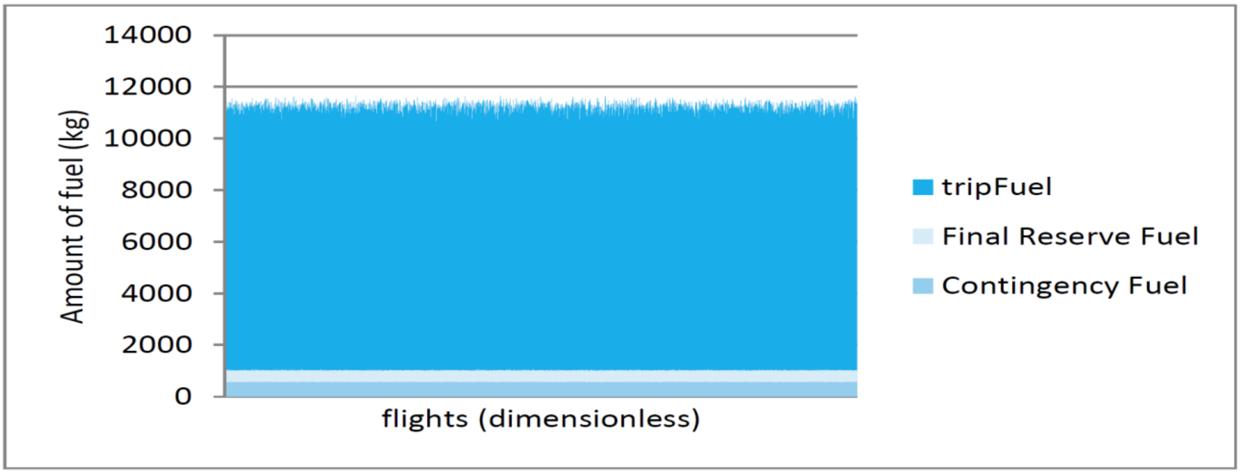


Figure 14 Trip, Contingency and Final Reserve Fuel for a specific flight route operated by A320

Finally, after running one MC simulation of 200.000 runs (flights), we observed a total of 4 fuel emergencies (MAYDAY fuel). In particular, all flights declared a fuel emergency eventually diverted to the alternate airport. The reason for the emergency declaration was in all cases the delays at the destination airport. The Flight Crew calculated the fuel upon landing if insisting on landing at the destination airport, resulting in a quantity below FRF. This is why an emergency was declared. Following this, Flight Crew made the decision of diverting, as it was decided not to hold by burning the alternate fuel, choosing the nearby alternate airport. This is actually the Flight Crew decision expected to be made, as our model describes, verifying the correctness. Finally, we see that all flights managed to land above FRF, and hence, not ending with an incident.

Table 16 Fuel emergencies for 200.000 flights

S/N	X-coord. of the dest. airport	Y-coord. of the dest. airport	X-coord. of the arrival airport	Y-coord. of the arrival airport	Total Fuel uplift (Kg)	Alternate Fuel Uplift (Kg)	Remaining fuel (after arrival) (Kg)	FRF (Kg)
54585	65	4	62	5	13200	933	1835	953
96992	67	6	64	5	13200	890	1185	929
163050	67	6	63	6	13200	916	1660	950
184833	67	6	63	6	14400	933	1645	986

4.2.3 Validation

Validation involves the testing of the model output to ensure that conforms to reality. The validation process of the simulation code was performed, exactly as for verification, for all agents and all variables, ensuring that the outputs are not just the expected, but also are the same with reality. In this section we will demonstrate some validation examples for some variables. We may start by explaining that as all parameters values are validated and explained throughout the model at the respective parameters' tables, and as the model is verified, we could only expect realistic values. Indeed, running the model we validated in various ways (debugging mode variables monitoring, variables outputs, and graphs).

As a first example, we will demonstrate the validation of the fundamental flight variables of the graph shown in Figure 12. By finding the same variables graph of a random real flight of similar route distance and same aircraft type from a popular ADS-B data tracking website Flight Radar 24, we were able to make the comparison of the two graphs. The similarity between the graphs is obvious and, as such, our flight model can be validated. In both graphs, the left vertical axis' unit is in feet, the right vertical axis's unit is in knots, and the horizontal axis is time (hour of the day in Flight Radar 24 graph, 5-minutes intervals in our graph).

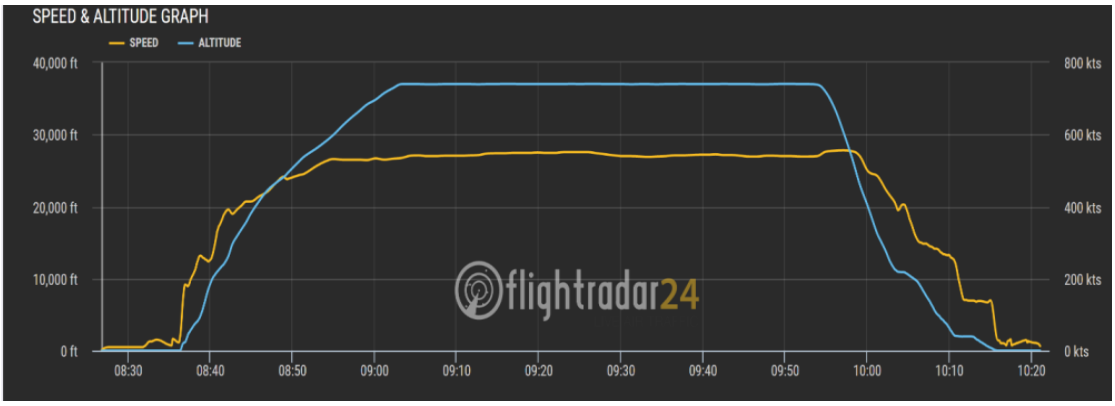


Figure 15 A real-flight altitude vs time vs ground speed graph

As a second example, the validation of the taxi and contingency fuel of the Figure 13 is presented: We validated the taxi fuel uplift amounts with [40] and [41]. Indeed, we see that for a flight with the same aircraft type between two European airports, the amount of fuel calculated for taxi lies around the mean value of the Figure 13. In addition, the amount of contingency fuel lies in a similar value. Similarly, in [41], we see similar values for the taxi variable. Following similar processes, we validated all the variables, ensuring that our model produces realistic results.

4.3 Simulation acceleration method

4.3.1 Introduction

Due to the fact that one of the events investigated (fuel exhaustion) is considered to be rare, straightforward Monte Carlo simulation turns to be not sufficient, due to computational time reasons. Despite our effort to shrink the computational time as possible by applying algorithmic techniques and by setting a large time step (1 min), we were limited to conduct ~10^7 straightforward Monte Carlo simulation runs.

As we face a rare-event problem, it was expected that an acceleration simulation technique would be required. Choosing and implementing the most appropriate acceleration method towards reaching the rare event more efficiently is not trivial. Several constraints –related to computational time, the problem’s nature, the amount of the variables, but also the actual project plan time available – were imposed. Having already achieved to minimize the computational time through algorithmic techniques (elimination of the “for” loops as possible, use of Java stream) at a level that it was feasible to run ~10^7 flights in reasonable computational time (1-2 days), we should apply a method that would render us capable of catching the rare event. As described in 3.1, the fuel exhaustion event is very rare and thus is expected to have an occurrence frequency of fewer than 10^{-9} flights. This means that we lack a factor of at least 10^4, to reliably assess the probability of the rare event. To manage this factor and reach this probability, an acceleration algorithm should be developed. As also stated in [42], reach probability estimation is well studied in the safety domain and is evaluated by using a finite partition method or by using Monte Carlo (MC) simulation. For realistic applications, the latter requires support from analytical methods to accelerate the simulation.

In the direction of accelerating our simulation, we chose to employ an Interacting Particle System (IPS) [43] with Bernoulli sampling [42].

4.3.2 The method

IPS is an acceleration method that is proven to be a useful tool in the identification of rare event probabilities. Blom [42] has shown that in the IPS algorithm for an arbitrary GSHS, Bernoulli sampling is essentially a better choice than a homogeneous Poisson process. The effectiveness of IPS in rare event estimation for simple diffusion examples in aerospace has been shown in [44]. Blom et al. [43], [45] applied IPS to rare event estimation for a GSHS model of an advanced air traffic scenario.

A simplified illustration of the IPS approach is shown in Figure 16, where m particles (A_1 to A_m) represent the complete hybrid state space of the agent-based model in m MC simulation runs. Particle A_3 hits the first fuel condition boundary (while the others do not hit the boundary) and its hybrid state space sets the basis for a next sequence of MC simulation runs. These MC simulation runs are executed until a new hit of the second boundary is done, etc.

In the implemented IPS method we define a series of decreasing remaining fuel quantities, $f_j < f_{j-1},\ j = 1,\ldots,i$, where i denotes the total number of the boundaries, with the additional (obvious) condition that the aircraft is still flying. N_1 runs of MC simulations of a specific scenario are sequentially conducted. The first simulation cycle stops when the first boundary has been hit H_1 times.

We define the fraction $\gamma_1 = H_1 / N_1$, which is the probability of reaching the first boundary. Before continuing to the next step, in which we continue the simulation of the particles that hit the first boundary, k_1 independent copies are drawn from the H_1 end states of the particles that have reached the first boundary. This is repeated from boundary 1 to boundary 2, by running N_2 times the total of $H_1 \cdot k_1$ particles to get $\gamma_2 = H_2 / N_2$, then from boundary 2 to boundary 3 to get $\gamma_3 = H_3 / N_3$, etc. until we reach the last boundary i and get $\gamma_i = H_i / N_i$. The probability of reaching the last boundary i is estimated as:

$$P = \prod_{m=1}^{i} \gamma_m$$

It has been proven [46] that this estimator converges to the true value under the condition that the simulated process satisfies the strong Markov property. This property means that at any stopping time, the future is conditionally independent of the past, given the present. As the developed risk model is an SDCPN model, it satisfies indeed the strong Markov property [47].

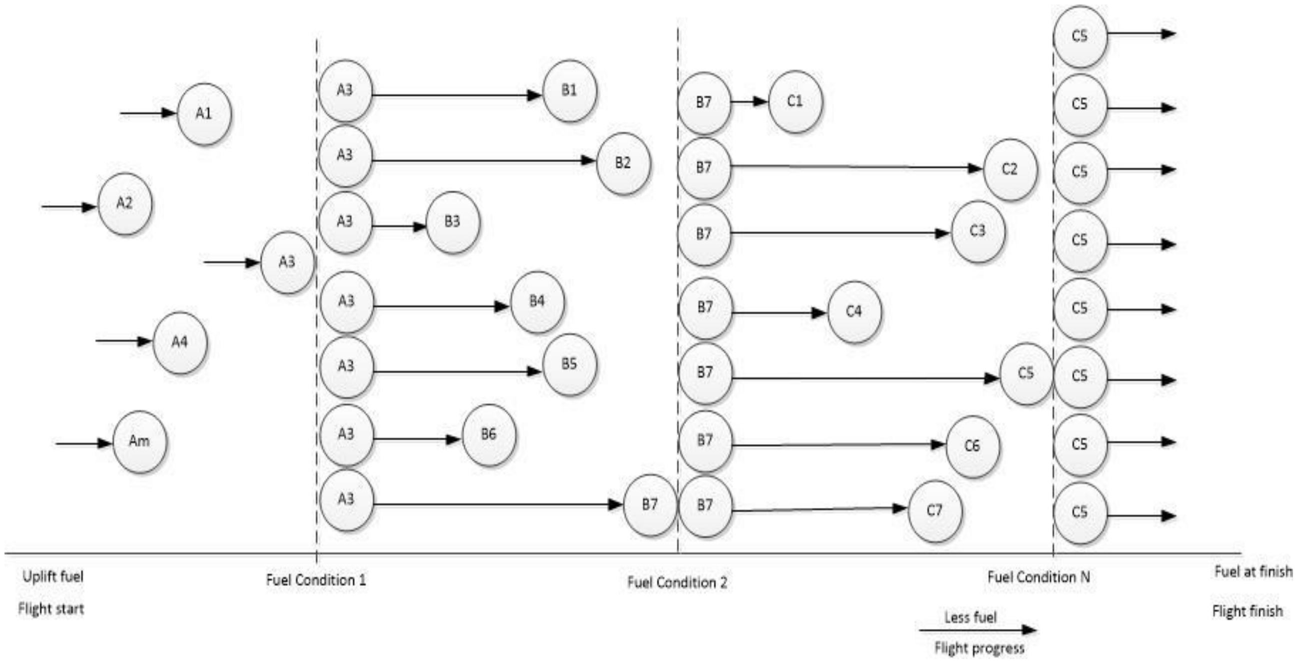


Figure 16 IPS method illustration

4.3.3 Implementation

After the comprehension of the method, the implementation in Java was performed. This was done by creating the classes MonteCarloIPS, which includes our development of the algorithm, and SimulationIPS, which is the risk model adjusted for the IPS method. In essence, the risk model is exactly the same, apart from some additions related to the boundaries and the flight variables saving. Moreover, in all agents and non-agent entities, one more method was implemented.

In particular, the algorithmic implementation of the method was split into three problems:

- How the model variables would be saved when a layer was hit?
- How the saved variables would be acquired in the next simulation step?
- How all these variables would be saved for the final simulation?

Despite these questions may seem naïve, eventually several computational constraints arose. Answering the first question, the variables that were needed for the continuation of the simulation are saved in an object of a new java class which was created for this reason; namely, class Level. In the following lines we will provide the description of our implementation: As long a layer is hit by a flight, all variables are saved in an object of the class Level. This process is repeated for all flights hit the first level. Hardware-wise, the variables are now saved in RAM. This is a very important notice, as it provides one very strong advantage, bus also an important limitation: RAM is very fast, and as such, the continuation of the simulation for the next levels is significantly faster. Despite that, as the number of variables is quite large, considering also the environment variables (4-D matrices), we were imposed "heap memory" constraints; this constrains imposed a maximum number of initial particles (flights) to be around 300. Otherwise, heap memory issues arise and the simulation crashes. It is of importance to mention that heap memory problems arise independently of the computer's hardware, as it is a common limitation amongst the programming languages. As now the variables are saved in RAM memory through objects of the class Level, there are easy and quickly accessible, rendering the consequent simulation steps faster.

4.3.4 Determination of the number of boundaries and their conditions

After having implemented the IPS method, we should determine the most appropriate number of layers, as well as the conditions of the layers, in the direction of catching the rare event. As NLR experts consulted, this is a trial and error process with no explicit rules.

The layer conditions selected from the first place was the amount of fuel left on board, interpreted into flight time. In specific, this was implemented as a factor multiplied by the Final Reserve Fuel of the specific flight. The conditions, therefore, are of the form "aeroplane is still flying" and "fuel left is less than $a \cdot f_{FRF}$", where a is a parameter and f_{FRF} equals thirty minutes of flight for the specific aircraft type. This condition is considered valid as satisfies the demand that the layer is the same for all particles.

The determination of the number of boundaries and the corresponding parameter a for each one was not a straightforward procedure; several trial-and-error simulations were run towards identifying the most proper boundaries for our problem. In the following lines we will demonstrate the process followed and how we ended up with the most efficient selection.

4.3.4.1 The problems faced

The most prominent issue arose during the calibration of the method was the constraints set by the heap memory. Indeed, this is a problem that cannot be eventually overcome and it is not a hardware issue. The implications of this constrain is the number of particles (aeroplanes) which we expect to hit the very first level; the number of hits for this level was limited to approximately 300 per simulation run. This happened because the largest agent, in terms of memory usage, is the environment (EN) non-agent (4D matrix of dimensions 170x30x15x70), which is created once at the beginning of the simulation. As long as a particle starts the simulation and hits the first level, before continuing to the next, all variables (including the environment variables) of the particles are saved. As the implementation of the method included the saving in the RAM memory, we were limited to save up to approximately 300 particles per simulation. After that level, saving the environment agent was not being saved anymore, as it was already saved in the first level and we could use it (by calling it) from there. This means that, in memory terms, the vast majority of our needs were allocated at the very first level. This fact is crucial for our simulation method, as the first level determines the number of particles of the entire simulation, which as mentioned, were limited. Therefore, we had two options:

1) Start with a relatively low fuel level, so only a very small percentage of the initial particles could hit.
2) Save the variables in the hard drive (HD) instead of RAM.

Starting with (2), it was clear that saving the variables in the HD eventually revealed that the computational time increases rapidly. Thus, we would not be able to reach the rare event. Therefore, (1) would possibly be the right choice. Indeed, starting with a low amount of fuel level proved to be the correct choice. Moreover, as our problem is not highly stochastic, setting a relatively low level of fuel as the first level was not problematic. Finally, the greatest advantage of following the first option was that, after the completion of the first level hits, RAM memory variables were accessed very fast and as such, the computational time was expedited by a large factor.

After that, we should set and calibrate the conditions of the next levels. The maximum number of hits of the next levels is directly connected to the heap memory left, and as such, with the number of hits of the first level. Despite that, the number of hits for around 250 hits on the first level would allow thousands of hits in the next levels, and hence, this was finally the number of maximum hits that we used.

The conditions' selection for the next levels was a long trial and error process. Very soon we realized the main problems: If the selection of the parameter a of the condition $a \cdot f_{FRF}$ of two consecutive levels were too close, all particles would hit. On the other side, if they were too far, no particle would hit. Hence, the selection of the parameter, as presented in each scenario analysis later in Chapter 895, is a result of several trials for the best results in reasonable computational time (some days).

4.3.5 Validation of the IPS

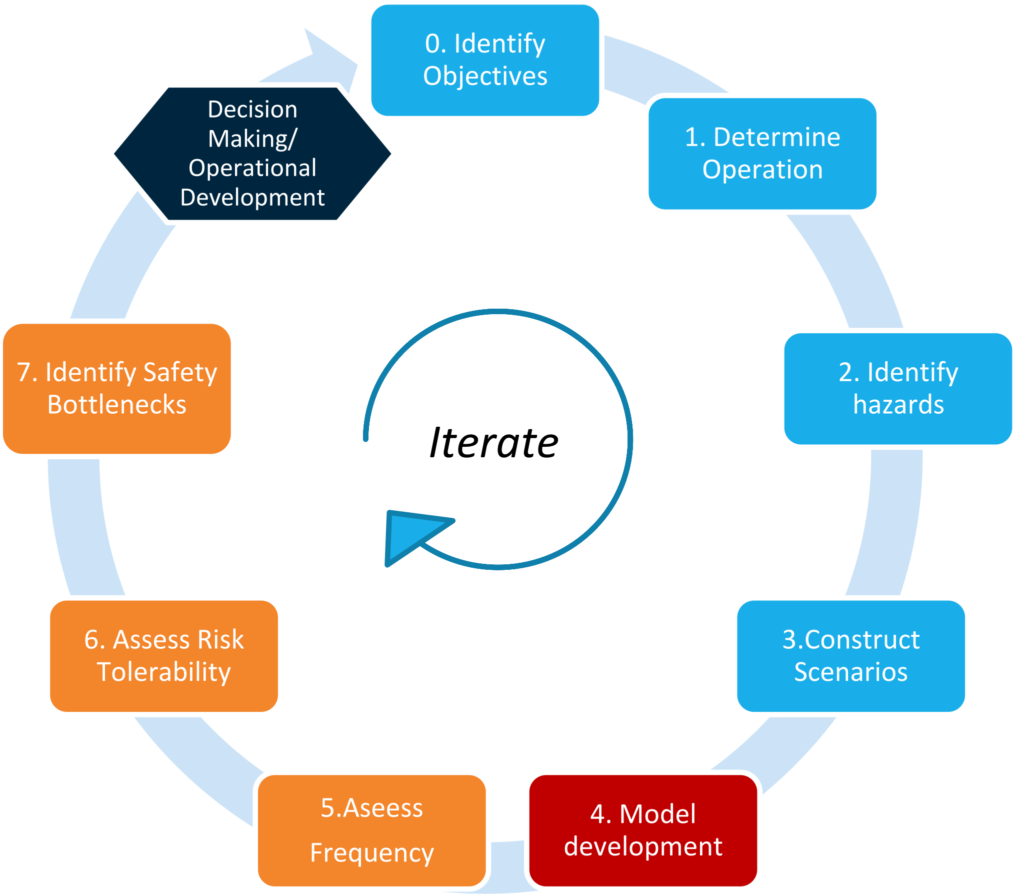
The validation of the IPS is performed through the comparison of the straightforward Monte Carlo simulation results. Trying to estimate the probability of the event "landing after consuming a portion of the FRF" through the IPS, provided us similar results with the straightforward Monte Carlo, validating the correctness of our IPS method.

4.4 Hardware used for the simulation

The hardware used for the simulation was the NLR’s High-Performance Computing units. The hardware characteristics of the High-Performance computing units rendered possible to run the simulations, using the advantages of parallel computing. In specific, a total of two remotely accessible computers were used. The hardware comprises a 40-core 196GB RAM unit and a second independent 20-core 112GB RAM unit. It is of importance to notice that for such simulations, the available computer power was extremely useful, in computational time terms.

5 Quantitative Safety Risk Assessment (steps 5-7)

In this Chapter we will demonstrate and analyze the results of the MC simulation. In particular, the estimated probabilities of the two events understudy will be illustrated. All scenarios' simulations are executed by employing both straightforward MC simulation and accelerated MC simulation with the IPS method. Furthermore, we will evaluate and assess the identified conflict scenarios on their severity, risk tolerability, while potential safety bottlenecks are identified and presented.



5.1 Evaluation of Frequency

In this section we will evaluate the frequency (probability) of occurrence of the three scenarios that have been identified in section 3.4, namely the medium-range flights, the long haul flights and last, the ETOPS flights. In the direction of presenting our results, it is needed to estimate the frequencies' errors or confidence intervals; we consider our experiments to be of a binomial distribution type with parameters n and p, where n is the number of runs per independent experiment and p is the discrete probability distribution of the number of successes. For all experiments we will calculate a 95% confidence interval. As the central limit theorem states, provided a sufficiently large random sample from the population with replacement, then the distribution of the sample will be approximately normally distributed. The confidence intervals throughout this section are estimated with $p \pm z_{1-\alpha/2}\sqrt{\frac{p(1-p)}{n}}$, where:

- p is the calculated probability
- n is the sample size
- α is the desired confidence
- $z_{1-\alpha/2}$ is the "z value" for the desired level of confidence
- $z_{1-\alpha/2} = 1.96$ for 95% confidence.

In our analysis, we examine two events: The first refers to landing (successfully) below the FRF, while the second refers to fuel exhaustion. Landing below the FRF is not as rare as the fuel exhaustion event. Thus, as explained in detail in 4.3.1, straightforward Monte Carlo simulation proved to be sufficient for studying the first event (successful landing below FRF) only. On the contrary, fuel exhaustion is a very rare event and its expected occurrence frequency is lower than 10^{-9} flights. This means that straightforward Monte Carlo is not sufficient (as also explained in in detail in 4.3.1). As such, the IPS method is employed for the second event (fuel exhaustion).

5.1.1 Scenario 1: Medium-Range Flights

Scenario 1 involves continental medium-range flights, executed by two aircraft types: Airbus 320 and Boeing 737. In this scenario, we consider normal flight planning regulations (no special requirements) and at least three airports located at a short distance (<200km) during the flight. Finally, we also perform a sensitivity analysis for Scenario 1, as described later in this section.

Final Reserve Fuel event using MC simulation

Initially a total of 30 straight-forward MC simulations were performed. Each MC simulation has 2 million runs (flights); hence, a total of 60 million flights were simulated. The number of simulations is roughly two orders of magnitude greater than the expected (based on previous research [37]) frequency of the event occurrence. Each run's duration takes approximately 12 hours. Thanks to the available computational power, we were able to run the simulations simultaneously. The observations of the event under study occurred during the simulation are demonstrated in the Table 17 below.

Table 17 Simulation results and calculated probabilities for medium-range flights, studying the event "landing below FRF"

Total number of flights simulated	Number of observations of the event	Event's probability	Confidence interval
$6\cdot10^{7}$	180	$3.0\cdot10^{-6}$	$(2.6\cdot10^{-6},\ 3.4\cdot10^{-6})$

Comments

Commenting on the simulation results of the first scenario, we may conclude that the probability of occurrence of the event under study lies in the area of 3 events per 1 million flights. For a single, medium-size airline (60 aircraft), the event would be expected to happen once every 3 years. Finally, the results differ substantially (by two orders of magnitude) from previous research on the topic [37].

Fuel Exhaustion event using IPS

To study this event (fuel exhaustion), we executed MC simulations with the employment of the acceleration method (IPS). The IPS parameters chosen are illustrated in the Table 18 below. The reasoning behind the choices of the parameters is presented in section 4.3.4.

Table 18 IPS method parameters for medium-range flights, studying the event "fuel exhaustion"

Number of initial IPS particles (flights)	Number of IPS levels	Condition of Level 1	Condition of Level 2	Resamples at level 1
$3\cdot10^{6}$	2	Amount of fuel left is less than 1.2 times the Final Reserve Fuel amount	No fuel left	$3.3\cdot10^{5}$

The event's observations of this simulation are demonstrated in Table 19, along with the probabilities' estimations.

Table 19 Simulation results and calculated probabilities for medium-range flights, studying the event "fuel exhaustion"

Number of observations at level 1	Number of observations at level 2	Total number of flights simulated	Probability reaching level 1	Probability of reaching level 2 (fuel event)	Confidence interval
38	82	$1\cdot10^{12}$	$1.2\cdot10^{-5}$	$8.2\cdot10^{-11}$	$(6.4\cdot10^{-11},9.9\cdot10^{-11})$

Comments

Commenting on the simulation results on the second event of the first scenario, we may conclude that the probability of occurrence of the event under study lies in the area of 3 events per 10 billion flights. This is at least one order of magnitude more (better) than the Target Level of Safety set for Commercial Air Transport operations, as described in Chapter 3. Despite this number seems to be very small, it is believed that it really corresponds to the actual operations; indeed, from the total number of fatal accidents, only a very small portion is accounted to the event under study (fuel exhaustion). Even the major aviation organizations, as described in Chapter 3, do not consider fuel exhaustion anymore in the top 10 accident causes. As such, the estimated accident rate seems plausible.

5.1.1.1 Sensitivity analysis for scenario 1

This section demonstrates a sensitivity analysis for scenario 1. The variable under sensitivity analysis is the FRF amount. The FRF amount for this scenario is set to 25min.

Sensitivity analysis for Final Reserve Fuel event using MC simulation

As before, 30 straight-forward MC simulations were performed. Each run simulated 2 million flights; hence, a total of 60 million flights were simulated. Each run's duration takes approximately 12 hours. In Table 20, we demonstrate the results of the simulation.

Table 20 Simulation results and calculated probabilities of sensitivity analysis (25min) for medium-range flights, studying the event "landing below FRF"

Total number of flights simulated	Number of observations of the event	Event's probability	Confidence interval
$6 \cdot 10^{7}$	209	$3.5 \cdot 10^{-6}$	$(3.0 \cdot 10^{-6},\ 3.9 \cdot 10^{-6})$

Comments

Given the simulation results of the sensitivity analysis scenario 1, we may conclude that the probability of occurrence of the event under study lies in the area of 3.5 events per 1 million flights. This is just above and within the confidence interval of the original results of scenario 1. Further discussion on this result, as well as comparison and possible explanations, are provided at the end of this section, under the "Results Comparison of scenarios 1" title.

Sensitivity analysis for Fuel Exhaustion event using IPS

For this event study, we executed MC simulations with the employment of the acceleration method (IPS). The IPS parameters chosen are illustrated in Table 21.

Table 21 IPS method parameters of sensitivity analysis (25min) for medium-range flights, studying the event "fuel exhaustion"

Number of initial IPS particles (flights)	Number of levels	Condition of Level 1	Condition of Level 2	Resamples at level 1
$1 \cdot 10^6$	2	Amount of fuel left is less than 1.1 times the Final Reserve Fuel amount	No fuel left	$1 \cdot 10^7$

The event's observations of this simulation are demonstrated in Table 22, along with the probabilities' estimations.

Table 22 Simulation results and calculated probabilities of sensitivity analysis (25min) for medium-range flights, studying the event "fuel exhaustion"

Number of observations at level 1	Number of observations at level 2	Total number of flights simulated	Probability of reaching level 1	Probability of reaching level 2 (fuel event)	Confidence interval
24	1401	$1 \cdot 10^{13}$	$2.4 \cdot 10^{-6}$	$1.4 \cdot 10^{-10}$	$(1.3 \cdot 10^{-10}, 1.5 \cdot 10^{-10})$

Comments

Commenting on the simulation results on the second event of the first scenario, we conclude that the probability of occurrence of the event under study lies in the area of 1 event per 10 billion flights. This is one order of magnitude more (better) than the Target Level of Safety set for Commercial Air Transport operations, as described in Chapter 3.

5.1.1.2 Additional sensitivity analysis for scenario 1

This section illustrates constitutes sensitivity analysis for scenario 1. The variable under sensitivity analysis is the FRF amount. The FRF amount for this scenario is set to 35min.

Sensitivity analysis for Final Reserve Fuel event using MC simulation

A total of 30 runs of straight-forward MC simulations were performed. Each run simulated 2 million flights; hence, a total of 60 million flights were simulated. Each run's duration takes approximately 12 hours. In

Table 23, we demonstrate the results of the simulation.

Table 23 Simulation results and calculated probabilities of sensitivity analysis for medium-range flights, studying the event "landing below FRF"

Total number of flights simulated	Number of observations of the event	Event's probability	Confidence interval
$6 \cdot 10^7$	167	$2.8 \cdot 10^{-6}$	$(2.2 \cdot 10^{-6},\ 3.3 \cdot 10^{-6})$

Comments

Given the simulation results of this sensitivity analysis for scenario 1, we can conclude that the probability of occurrence of the event under study lies in the area of 3 events per 1 million flights. Further discussion on this result, as well as comparison and possible explanations, are provided at the end of this section, under the "Results Comparison of scenarios 1" title.

Sensitivity analysis for Fuel Exhaustion event using IPS

As before, for this event study we executed MC simulations with the employment of the acceleration method (IPS). The IPS parameters chosen are illustrated in Table 24.

Table 24 IPS method parameters of sensitivity analysis (35min) for medium-range flights, studying the event "landing below FRF"

Number of initial IPS particles (flights)	Number of levels	Condition of Level 1	Condition of Level 2	Resamples at level 1
$2 \cdot 10^{6}$	2	Amount of fuel left is less than 1.1 times the Final Reserve Fuel amount	No fuel left	$5 \cdot 10^{6}$

The event's observations of this simulation are demonstrated in Table 25, along with the probabilities' estimations.

Table 25 Simulation results and calculated probabilities of sensitivity analysis for medium-range flights, studying the event "fuel exhaustion"

Number of observations at level 1	Number of observations at level 2	Total number of flights simulated	Probability of reaching level 1	Probability of reaching level 2 (fuel event)	Confidence interval
19	618	$1 \cdot 10^{13}$	$9.5 \cdot 10^{-6}$	$6.2 \cdot 10^{-11}$	$(5.7 \cdot 10^{-11}, 6.7 \cdot 10^{-11})$

Comments

Commenting on the simulation results on the second event of the first scenario, we may conclude that the probability of occurrence of the event under study lies around 6 events per 100 billion flights. This is two orders of magnitude more (better) than the Target Level of Safety set for Commercial Air Transport operations, as described in Chapter 3.

Results comparison for scenario 1

In this paragraph we will compare the sensitivity analysis and the original results. For the facilitation of the reading, the various results are summarized and presented in Table 26 and Table 27 below. It can be seen that, concerning the study of the first event (Table 26), there are no significant differences amongst the frequencies estimates. In particular, sensitivity analysis for

FRF=35min demonstrates the lowest estimate, for sensitivity analysis for FRF set to 25min the highest and, finally, the original scenario lies near the average value. Moreover, we should mention that all estimations lie inside the confidence intervals of the other estimation. In addition, it should be noted that all results satisfy the target level of safety as set in section 3.1. A plausible explanation on why there are no larger differences between the estimation is that, despite there is more (or less) fuel available during the simulated flights of the sensitivity analysis, as FRF amount is set to a higher (lower) level, it is easier (more difficult) to reach it. As such, it is of higher interest to compare the second event differences, rather than the first one.

Table 26 Summary of calculated probabilities for medium-range flights, studying the event "landing below FRF"

FRF amount (min)	Event's probability	Confidence interval
30	$3.0 \cdot 10^{-6}$	$(2.6 \cdot 10^{-6},\ 3.4 \cdot 10^{-6})$
25	$3.5 \cdot 10^{-6}$	$(3.0 \cdot 10^{-6},\ 3.9 \cdot 10^{-6})$
35	$2.8 \cdot 10^{-6}$	$(2.2 \cdot 10^{-6},\ 3.3 \cdot 10^{-6})$

Concerning the second event (summarized in Table 27) we can conclude that some significant differences are identified. Specifically, the sensitivity analysis for 35 minutes of FRF results implies a decline in the accident rate by a factor of 1.3. Moreover, the analysis of 25 minutes of fuel resulted in an increase in the accident rate by a factor of 1.7. Hence, we have identified the sensitivity of the FRF variable value. Finally, we should note that in all cases, the results are in conformance with the safety target for accidents, as set in section 3.1. The main conclusion of our results is that a slight increase (5min or about 150kg) in the FRF amount to 35min, would bring a small improvement in the accident rate; on the other hand, a slight decrease would imply a small, but double than before, increase in the accident rate.

Table 27 Summary of calculated probabilities for medium-range flights, studying the event "Fuel exhaustion"

FRF amount (min)	Event's probability	Confidence interval
30	$8.2 \cdot 10^{-11}$	$(8.1 \cdot 10^{-11}, 8.3 \cdot 10^{-11})$
25	$1.4 \cdot 10^{-10}$	$(1.3 \cdot 10^{-10}, 1.5 \cdot 10^{-10})$
35	$6.2 \cdot 10^{-11}$	$(6.1 \cdot 10^{-11}, 6.3 \cdot 10^{-11})$

5.1.2 Scenario 2: Long-Range Flights

Scenario 2 involves Long-range flights by three aircraft types: Airbus 330, Boeing 787 and Airbus 350. In this scenario we consider normal flight planning regulations (no special requirements) and at least one airport located at a medium distance (<800km) during the flight.

Final Reserve Fuel event using MC simulation

A total of 30 runs employing straight-forward MC simulations were executed. Each run simulated 2 million flights; hence, a total of 60 million flights were simulated. Each run's duration takes approximately 3 days. The observations of the event understudy of this scenario simulation are summarized in the

Table 28. Now, we may calculate the overall probability estimation.

Table 28 Simulation results and calculated probabilities for long-range flights, studying the event "landing below FRF"

Total number of flights simulated	Number of observations of the event	Event's probability	Confidence interval
$6 \cdot 10^{7}$	4	$0.7 \cdot 10^{-7}$	$(3.0 \cdot 10^{-9}, 1.3 \cdot 10^{-7})$

Comments

Commenting on the simulation results of the first event of the second scenario, we may conclude that the probability of occurrence of the event under study lies in the area of 1 event per 15 million flights. This is one order of magnitude less (better) than the respective event of scenario 1. Despite this number is quite small, it is not surprising. The examined scenario assumed long flights with several alternate airports available. This means that the aircraft carry a large amount of fuel, which can be used for any unpredicted case while en-route. Furthermore, as the contingency fuel is defined as a percentage of the trip fuel (5%), it means that the longer the trip, the larger this amount. As such, a great amount of fuel is finally uplifted, compensating for unpredicted cases and failures. Moreover, as the number of observations is very low, the confidence interval is respectively quite large.

Fuel Exhaustion event using IPS

To study this event, we executed simulation by means of simulation acceleration techniques (IPS method). To do so, we chose the following parameters, as shown in Table 29.

Table 29 IPS method parameters for long-range flights, studying the event "fuel exhaustion"

Number of initial IPS particles (flights)	Number of levels	Condition of Level 1	Condition of Level 2	Condition of Level 3	Resamples at level 1	Resamples at level 2
$1 \cdot 10^{6}$	2	amount of fuel left is less than 3.2 times the FRF amount	amount of fuel left is less than 0.9 times FRF amount	No fuel is left	$1 \cdot 10^{5}$	$5 \cdot 10^{5}$

In Table 30, we demonstrate the simulation results and the overall probability estimation.

Table 30 Simulation results and calculated probabilities for long-range flights, studying the event "fuel exhaustion"

Number of observations at level 1	Number of observations at level 2	Number of observations at level 3	Total number of flights simulated	Probability of reaching level 1	Probability of reaching level 2	Probability of reaching level 3 (event)	Confidence interval
35	46	435	$5 \cdot 10^{16}$	$3.5 \cdot 10^{-5}$	$4.6 \cdot 10^{-10}$	$8.7 \cdot 10^{-15}$	$(7.9 \cdot 10^{-15}, 9.5 \cdot 10^{-15})$

Comments

Commenting on the simulation results of the second event of the second scenario we may conclude that the probability of occurrence of the event under study lies in the area of 1 event per 90 trillion flights. This number is extremely small and could also be interpreted as a "will never happen" event. Following the same explanation given for event 1, indeed it is an extremely rare event which is extremely difficult to be realized. This is due to the abundance of alternate airports, the contemporary nature of the aircraft, and the very large amount of fuel carried onboard.

5.1.3 Scenario 3: ETOPS Flights

Scenario 3 involves the Long-range and ultra-long-range flights under ETOPS fuel planning requirements. The aircraft types considered for this type of operations are Airbus 330 (long-range), Boeing 787 and Airbus 350 (ultra-long-range). Two different ETOPS categories are simulated, namely ETOPS 240 and 370. Therefore, scenario 3 is split into the sub-scenarios 3a and 3b for ETOPS 240 and ETOPS 370 respectively. ETOPS scenarios are described in detail in section 3.4.

5.1.3.1 Scenario 3a: ETOPS 240

Final Reserve Fuel event using MC simulation

A total of 30 runs employing straight-forward MC simulations were executed. Each run simulated 2 million flights; hence, a total of 60 million flights were simulated. Each run's duration takes approximately 3 days. The observations of the event understudy of this scenario simulation are summarized in the

Table 31 below. Now, we may calculate the overall probability estimation.

Table 31 Simulation results and calculated probabilities for ETOPS 240 flights, studying the event "landing below FRF"

Total number of flights simulated	Number of observations of the event	Event's probability	Confidence interval
$6 \cdot 10^{7}$	118	$2.0 \cdot 10^{-6}$	$(1.6 \cdot 10^{-6}, 2.3 \cdot 10^{-6})$

Comments

Commenting on the simulation results of the first event of the scenario 3a, we may conclude that the probability of occurrence of the event under study lies in the area of 6 events per 1 million flights. This is one order of magnitude more (worse) than the respective event of scenario 2. This is quite expected, as the lack of alternate airport could lead in long-distance travelling in urgent cases. Finally, the estimated value and the lower value of the confidence interval, are both compliant with the safety target for incidents, as set in section 3.1.

Fuel Exhaustion event using IPS

To study this event, we executed MC simulations with the employment of the acceleration method (IPS). The IPS parameters chosen are illustrated in the Table 32 below.

Table 32 IPS method parameters for ETOPS 240 flights, studying the event "fuel exhaustion"

Number of initial IPS particles (flights)	Number of levels	Condition of Level 1	Condition of Level 2	Condition of Level 3	Resamples at level 1	Resamples at level 2
$1\cdot 10^{6}$	3	amount of fuel left is less than 3.3 times the FRF	amount of fuel left is less than 0.8 times the FRF	No fuel is left	$1\cdot 10^{5}$	$1\cdot 10^{5}$

The observations of the two events through the simulations are demonstrated in Table 33.

Table 33 Simulation results and calculated probabilities for ETOPS 240 flights, studying the event "fuel exhaustion"

Number of observations at level 1	Number of observations at level 2	Number of observations at level 3	Total number of flights simulated	Probability of reaching level 1	Probability of reaching level 2	Probability of reaching level 3 (event)
28	295	1570	$1\cdot 10^{16}$	$3.0\cdot 10^{-9}$	$1.6\cdot 10^{-13}$	$(1.5\cdot 10^{-13},1.7\cdot 10^{-13})$

Comments

Commenting on the simulation results of the second event of the scenario 3a, we may conclude that the probability of occurrence of the event under study lies in the area of 2 events per 10 trillion flights. This number is extremely small, and it is interpreted as both due to the very large amount of fuel carried, but, most importantly, due to the assumptions made for the ETOPS scenarios (no emergencies). Indeed, ETOPS flights are treated differently by the regulators, due to their nature, as explained in Chapter 3. The regulators give special attention to the cases of engine failure and cabin decompression, something that could not be considered in our model. As such, our estimations possible are lower than the real values, considering the assumptions.

5.1.3.2 Scenario 3b: ETOPS 370

Final Reserve Fuel event using MC simulation

A total of 30 runs employing straight-forward MC simulations were executed. Each run simulated 2 million flights; hence, a total of 60 million flights were simulated. Each run's duration takes approximately 3 days. The observations of the event understudy of this scenario simulation are summarized in Table 34. Now, we may calculate the overall probability estimation.

Table 34 Simulation results and calculated probabilities for ETOPS 370 flights, studying the event "landing below FRF"

Total number of flights simulated	Number of observations of the event	Event's probability	Confidence interval
$6 \cdot 10^{7}$	381	$6.4 \cdot 10^{-6}$	$(6.1 \cdot 10^{-6}, 6.8 \cdot 10^{-6})$

Comments

Commenting on the simulation results of the first event of the scenario 3b, we may conclude that the probability of occurrence of the event under study lies in the area of 6 events per 1 million flights. This is one order of magnitude more (worse) than the respective event of scenario 2; besides, it is significantly larger but in the same order of magnitude in comparison with the respective estimate of scenario 3a. This is expected, as the lack of alternate airport could lead in long-distance travelling in urgent cases, even larger than these of scenario 3a. Finally, the estimated value and the lower value of the confidence interval are both compliant with the safety target for incidents, as set in section 3.1.

Fuel Exhaustion event using IPS

To study this event, we executed MC simulations with the employment of the acceleration method (IPS). The IPS parameters chosen are illustrated in Table 35.

Table 35 IPS method parameters for ETOPS 370 flights, studying the event "fuel exhaustion"

Number of initial IPS particles	Number of levels	Condition of Level 1	Condition of Level 2	Condition of Level 3	Resamples at level 1	Resamples at level 2
$1 \cdot 10^{6}$	3	amount of fuel left is less than 3.6 times the FRF amount	amount of fuel left is less than 0.8 times the FRF amount	No fuel is left	$1 \cdot 10^{5}$	$1 \cdot 10^{5}$

The observations of the two events through the simulations are demonstrated in Table 36.

Table 36 Simulation results and calculated probabilities for ETOPS 370 flights, studying the event "fuel exhaustion"

Number of observations at level 1	Number of observations at level 2	Number of observations at level 3	Total number of flights simulated	Prob. of reaching level 1	Probability of reaching level 2	Probability of reaching level 3 (event)
28	1340	5816	$1\cdot10^{16}$	$1.3\cdot10^{-8}$	$5.8\cdot10^{-13}$	$(5.6\cdot10^{-13},5.9\cdot10^{-13})$

Comments

Commenting on the simulation results of the second event of the scenario 3b, we may conclude that the probability of occurrence of the event under study lies in the area of 6 events per 10 trillion flights. This number is extremely small, and it is interpreted in the same way we discussed the respective event of scenario 3a.

5.2 Risk Tolerability assessment

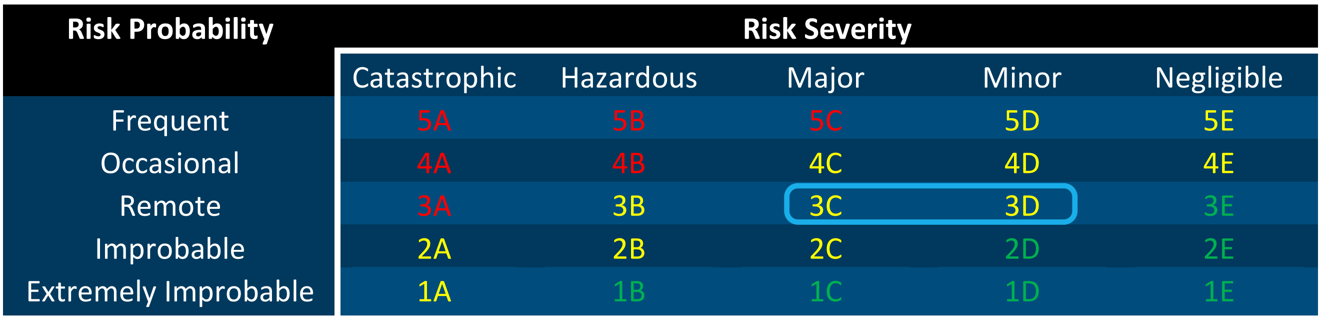
In this step, the probabilities and severities identified in the previous steps, will be combined on the risk acceptability (tolerability) matrix, to judge and decide over their acceptability. The acceptability matrix is explained in section 3.1. To classify the two events for the various scenarios, we highlight the respective areas. We use blue-coloured rectangles for event 1 (land below FRF) and orange for event 2 (fuel exhaustion). We notice that no unacceptable (red) area is identified. Finally, there is one combination for each scenario where mitigation is needed (yellow area).

Scenario 1: Medium-Range Flights

The events under study are classified in the same area of the acceptability matrix for scenarios 1 (FRF=30) and sensitivity analysis (FRF=25, 35) and, as such, are illustrated together.

Final Reserve Fuel event

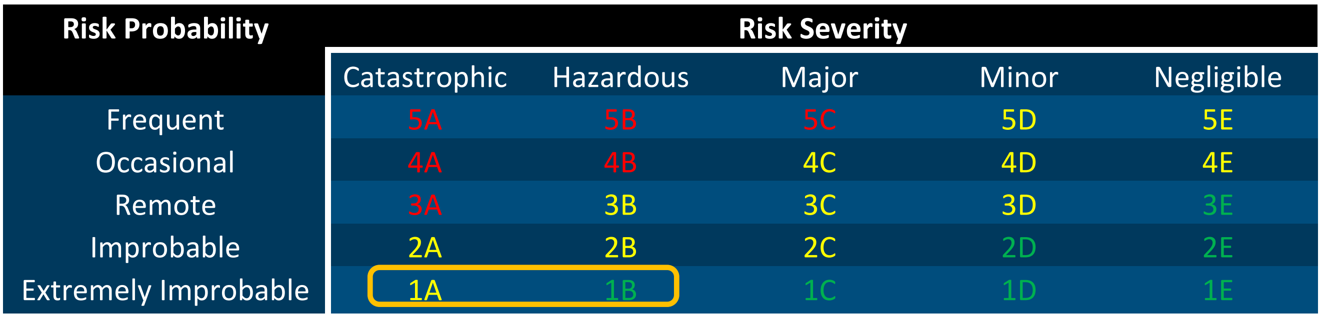
Table 37 Evaluation of the acceptability of the medium-range flights, studying the event "landing below FRF"



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

Fuel Exhaustion event

Table 38 Evaluation of the acceptability of medium-range flights, studying the event "fuel exhaustion"



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

Comments

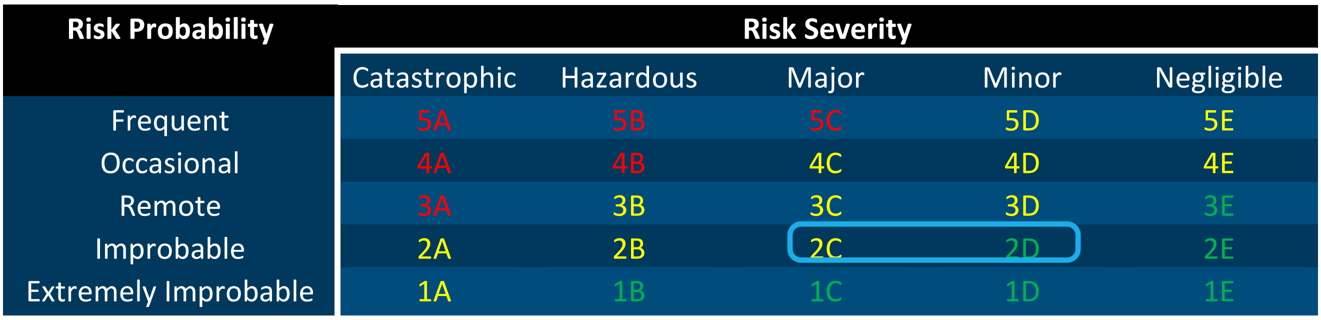
Regarding the first scenario (all sub scenarios), the first event is evaluated as yellow (3C and 3D), whilst the second as both yellow (1A) and green (1B). Therefore, the first event is classified as tolerable, while the second as either tolerable or acceptable.

Scenario 2: Long-Range Flights

The events' acceptability evaluation for the second scenario (long-range flights) are illustrated below.

Final Reserve Fuel event

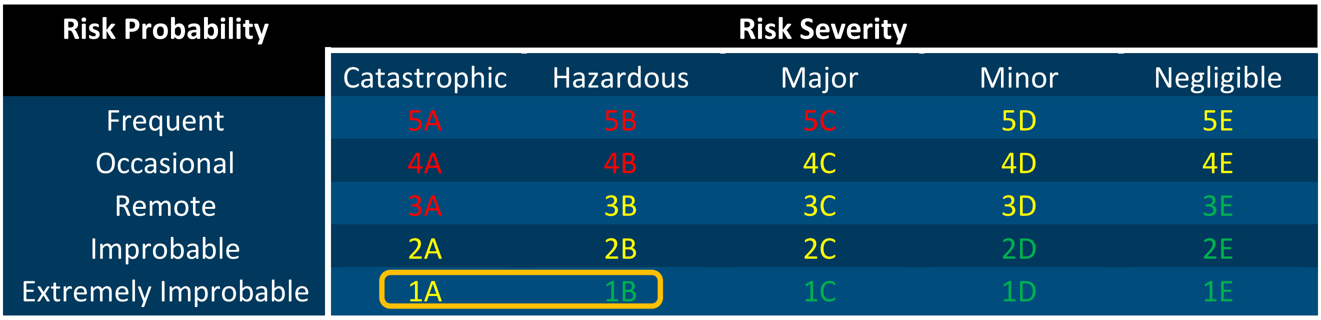
Table 39 Acceptability evaluation of long-range flights, studying the event "landing below FRF"



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

Fuel Exhaustion event

Table 40 Acceptability evaluation of long-range flights, studying the event "fuel exhaustion"



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

Comments

Concerning scenario 2, both events are evaluated as yellow and green; 2C and 2D for the first, 1A and 1B for the second event: Therefore, both events are classified as either tolerable or acceptable.

Scenario 3: ETOPS Flights

The events under study are classified in the same area of the acceptability matrix for both scenarios 3a and 3b and, as such, are illustrated together.

Final Reserve Fuel event

Table 41 Acceptability evaluation of ETOPS 240 and 370 flights (scenarios 3a and 3b), studying the event "landing below FRF"

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

Fuel Exhaustion event

Table 42 Acceptability evaluation of ETOPS 240 and 370 flights (scenarios 3a and 3b), studying the event "fuel exhaustion"

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

Comments

Concerning scenario 3, event 1 is evaluated as yellow (3C and 3D), while event 2 both as yellow (1A) and green (1B). Hence, both events are classified as either tolerable or acceptable.

5.3 Safety Bottlenecks Identification

During the simulation of the scenarios, all variables values have been saved into files for possible analysis of the events and, thus, for further research. This research comprises the identification of the bottlenecks that contributed to the events under study. Hence, we may identify which agents played a crucial role in the realization of the events. Amongst many flight variables, the following safety-relevant variables (shown in Table 43) were saved in the direction of the safety bottlenecks identification. The identification of the safety bottlenecks supports the consideration of the mitigating actions, if needed to be taken.

Table 43 Safety-relevant variables saved for the analysis

Distance planned vs travelled	Mayday declaration	FC planning sufficiency
Diversion (alternate) executed	Fuel leakage	Holding time
flight time planned vs travelled	Fuel upon landing	Increased fuel consumption
Airport and weather delays	Landing gear malfunction	Number of missed approaches
Airspace Avoidance	FC quality	Fuel asked vs Fuel uplifted
FC identified an on-going fuel issue	Runway change	ATC System condition
Airport runway change	ATC vectors quality	MRO factor provided to FC
Airport hazards groups active	Ground Handling time	

Some of the safety-relevant variables have been identified to contribute more frequently, as they are triggered more often. It is also identified that usually more than one hazard should be triggered for a unique flight to end up with a fuel-related event. Due to the big number of flights and variables, the following analysis focuses on the most prominent safety-relevant variables. The following analysis concern the flights resulted in a fuel-related event (land below FRF or fuel exhaustion).

5.3.1 Scenario 1: Medium-Range Flights

Event 1 (Landing below FRF)

Amongst the flights that ended up with less than the FRF amount (30min) upon landing, the following agents have contributed to the incident:

1. Flight Crew agent

65% of the Flight Crew did not divert to an alternate airport after identified the on-going fuel issue, while 11% of the Flight Crew did not declare an emergency (mayday). The reason for the diversion is mainly airport delays (operational or weather) or closed airport. Reason for not diverting is the unavailability of an appropriate alternate airport.

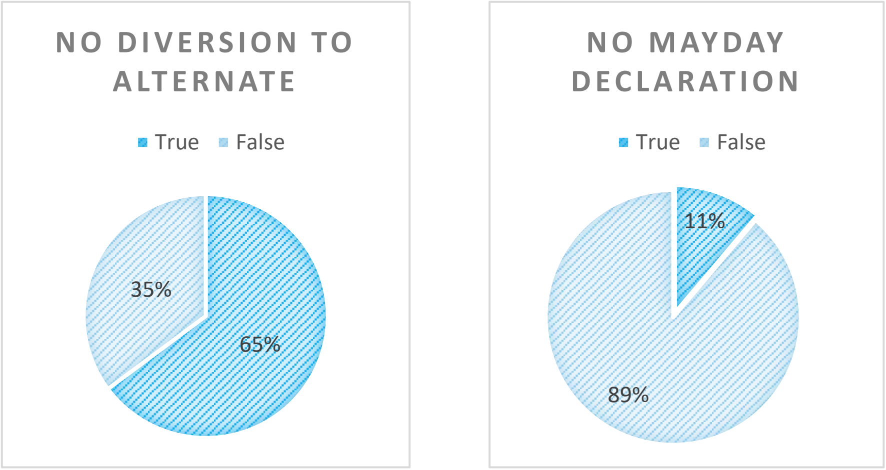


Figure 17 Bottlenecks associated with FC agent during medium-range flights

2. Aircraft agent

17% of the flights landed below FRF, experienced increased fuel consumption during the flight (due to icing or degraded engines/aerodynamics). Moreover, few flights had landing gear malfunctions (leading to missed approach).

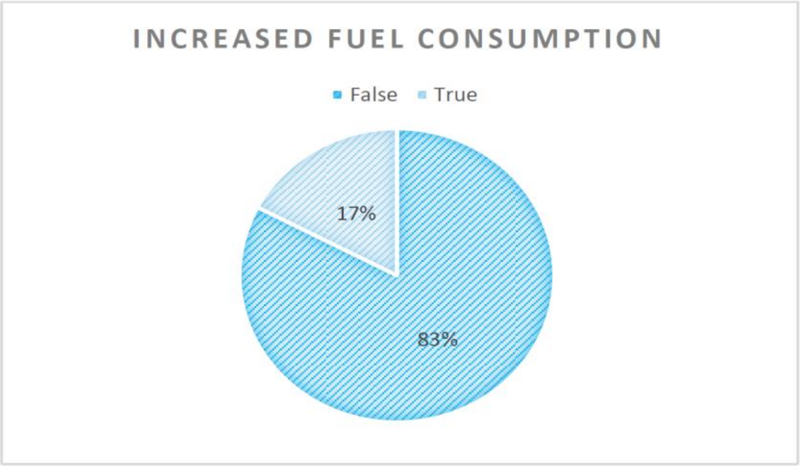


Figure 18 Bottlenecks associated with AC agent during medium-range flights

3. Airport and Environment (non) agents

Delays due to weather at airports or airports' operational delays were identified as a safety bottleneck, as they contributed to increased flight time and fuel events. 14% of the flights experienced holding due to weather and 16% of the flights due to airports' operational reasons.

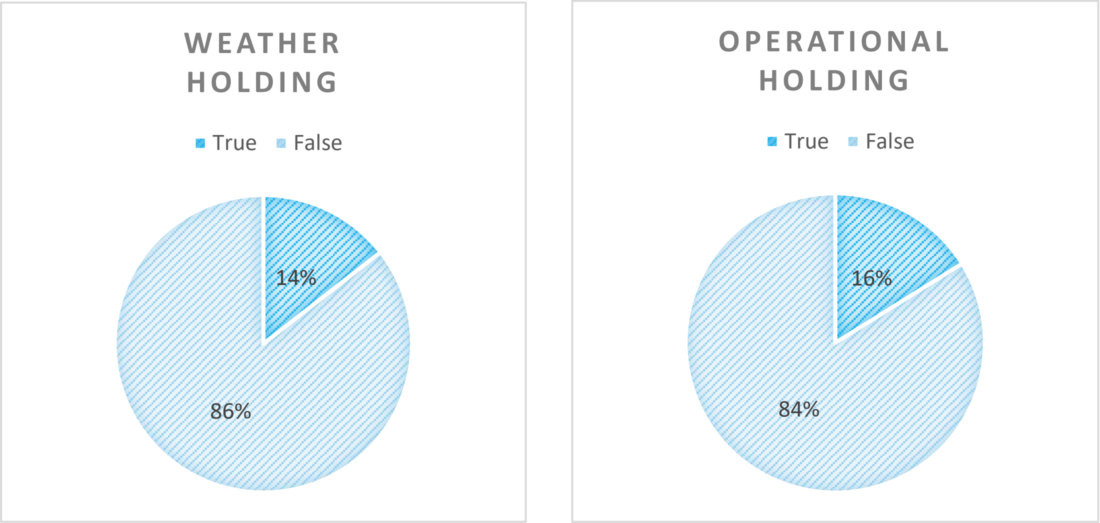


Figure 19 Flights entered holding due to Weather/Airports delays, resulting in fuel event.

Event 2 (Fuel Exhaustion)

Amongst the flights that ended up with fuel exhaustion, we found similar trends, as the same bottlenecks were identified. 29% of flights had increased fuel consumption, while 27% of flights did not declare the emergency. The reason for the increased flight time was mainly the airport operational delays and weather, as before.

5.3.2 Scenario 2: Long-Range Flights

Event 1 (Landing below FRF)

No bottlenecks can be safely identified due to the very small number of events.

Event 2 (Fuel Exhaustion)

1. Flight Crew agent

61% of the Flight Crew did not divert to an alternate airport after identifying the on-going fuel issue, while 16% of the Flight Crew did not declare an emergency (mayday).

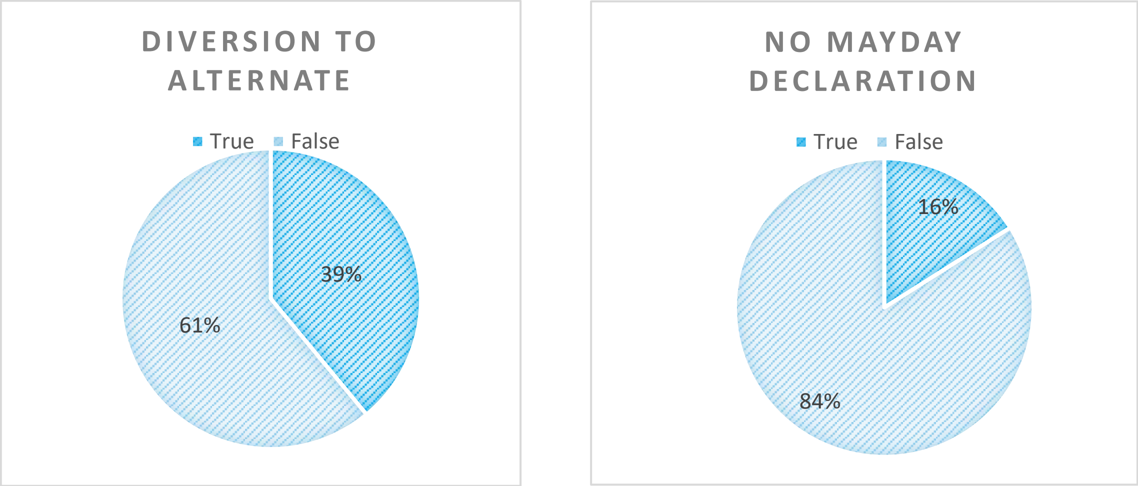


Figure 20 Bottlenecks associated with FC agent during long-range flights

2. Aircraft agent

Increased fuel consumption (due to icing or degraded engines/aerodynamics) happened to 14% of the flights experienced fuel exhaustion in the second scenario.

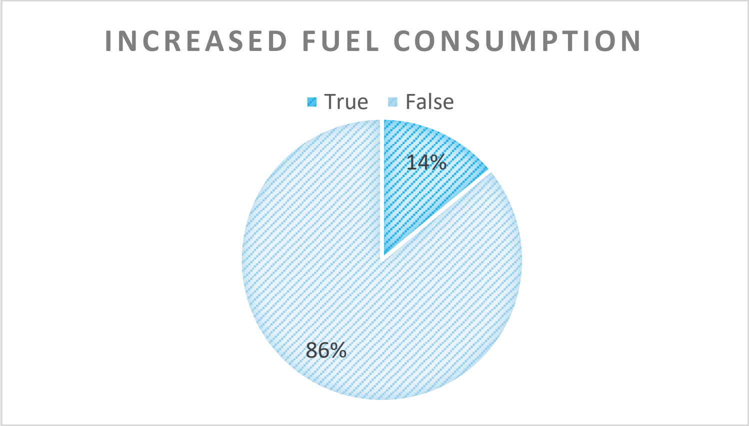


Figure 21 Bottlenecks associated with AC agent during long-range flights

3. Airport and Environment (non) agents

Holding times and percentage of flights proceeded to hold due to weather or operational reasons are very similar to scenario 1- event 2: Fuel exhaustion for medium-range flights

5.3.3 Scenario 3: ETOPS Flights

Event 1 (Landing below FRF)

Scenario 3 simulates ETOPS flights and, as such, unavailability of alternate airports during the cruise is the most important characteristic of the scenario. This is found to be crucial also in the bottlenecks' analysis. Amongst the flights that ended up with less than the FRF amount (30min) upon landing, the following agents have contributed to the incident:

1. Flight Crew Agent

Flight Crew did not divert to an alternate airport after identifying the on-going fuel issue for a 72% and 88% of flights, while 28% of the Flight Crew did not declare an emergency (mayday). Mayday declaration bottleneck appeared in almost the same percentage of flights in both ETOPS scenarios.

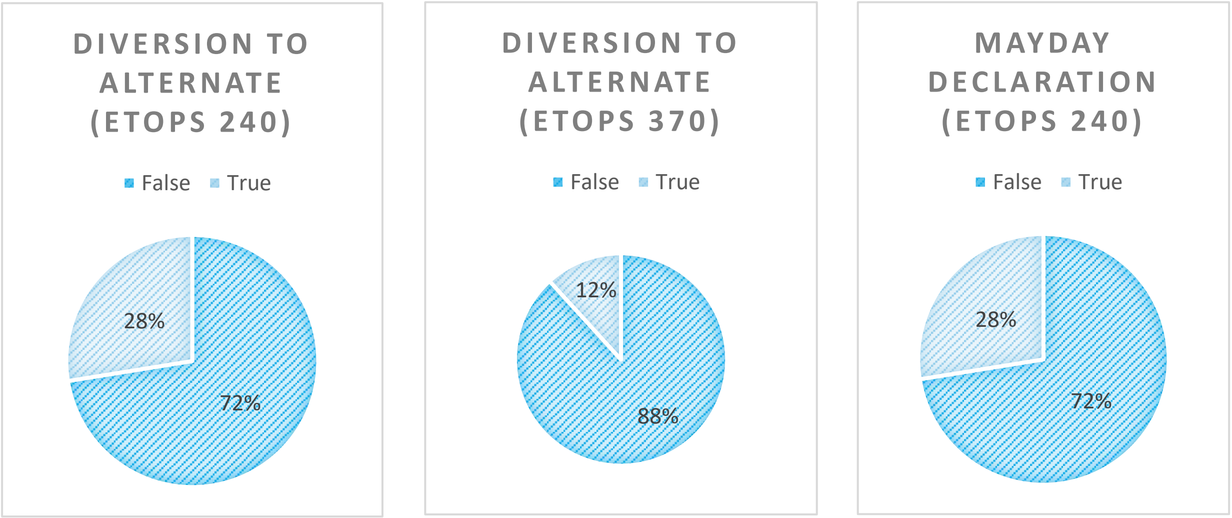


Figure 22 Bottlenecks associated with FC agent during ETOPS flights

2.Aircraft Agent

Increased fuel consumption (due to icing or degraded engines/aerodynamics) happened to 43% and 65% of the flights landed below FRF, for the two ETOPS scenarios respectively.

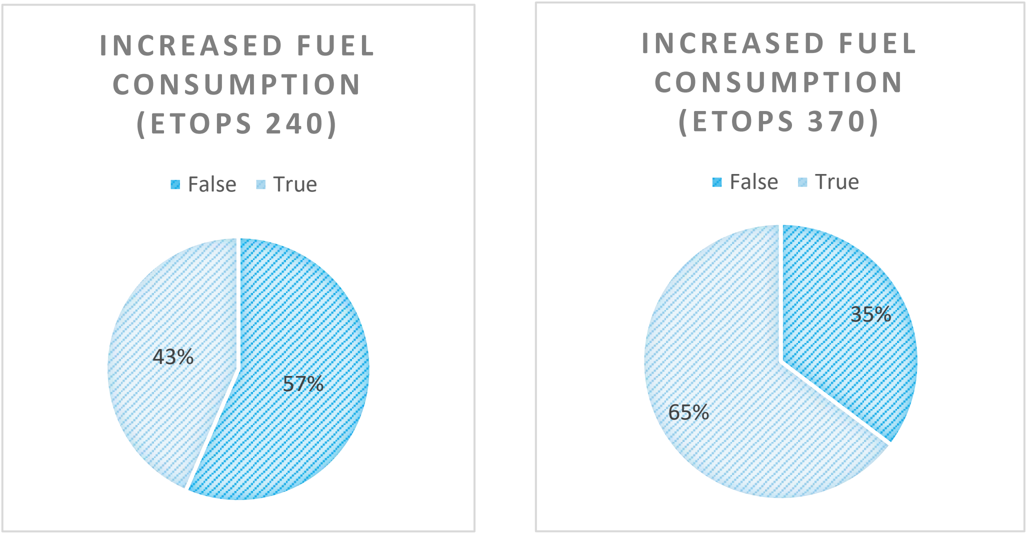


Figure 23 Bottlenecks associated with AC agent during ETOPS flights

Event 2 (Fuel Exhaustion)

Flights experienced fuel exhaustion were identified with very similar trends; the most prominent bottlenecks identified were the inability of deviation to an alternate (76% and 79% respectively increased fuel consumption (46% and 62% of the flights for ETOPS 240 and 370 respectively) and the non-declaration of an emergency situation (around 15% of the flights for both cases).

Safety bottlenecks identification conclusions

The analysis of this section led us to identify the most important safety bottlenecks, which are identified to be the following: non-declaration of an emergency, increased fuel consumption both due to engine or aerodynamic degradation, airport or weather delays and non-deviation to an alternate airport. The last bottleneck is determinant in the ETOPS scenarios, while it should be clarified that it is not a Flight Crew negligence, but inability (unavailability of appropriate airports). Airspace avoidance (due to weather or NOTAM), landing gear malfunction leading to missed approach and holding and ATC System failure (leading to long delays) have been also identified with a low frequency.

On the other hand, hazards such as fuel leakage, bad fuel planning, Air Traffic Controllers' bad vectoring, Ground Handlers fuelling mistakes and the rest of the variables from Table 43 have no or slight appearance throughout the simulations; therefore, they do not contribute substantially to the fuel events. Finally, no safety trends were identified with regard to the aircraft type.

6 Conclusions

In this Chapter we will demonstrate our conclusions over the entire study, as we all suggestions for further research. The foremost objective of this research project was to reliably estimate the probabilities of two conspicuous fuel-related aviation incidents and conduct safety risk assessment over these events. This has been accomplished as follows:

Starting with our regulations study, we thoroughly examined the fuel-related literature and regulations. In Chapter 2, we illustrated, compared and commented on the fuel planning and management regulations, as published by the most important aviation regulatory bodies. With the study of the regulation, it was recognized that the fuel planning process is a highly regulated area. However, some space is given to airlines to decide for contingencies, and this is where the airlines try to acquire a fuel efficiency benefit. Moreover, ICAO and EASA impose 30min reserve fuel for any flight, something not followed by FAA in all flights. The FRF amount of fuel is not further justified, providing opportunities for research and objections over this number. This is why we also employed a sensitivity analysis of this value.

We have also recognized that the regulations mostly concern the fuel planning phase, but also the fuel management phase. This is an important distinction, as in these cases airlines must comply with several in-flight fuel management rules. Overall, it was concluded that research should be employed to identify whether the fuel provisions for each case are adequate for the current operational environment.

Continuing with Chapter 3, the Quantitative Safety Risk Analysis was presented. Following the TOPAZ methodology step by step, initially, we set our analysis and assessment objectives and we clarified the operations under study. Next, a hazard list that was originally developed in previous NLR research [37] was extended and differently classified; finally, we illustrated the operational scenarios that would be considered; these scenarios were chosen with respect to the flight time, the aircraft type and the availability of alternate airports.

For the development of the safety risk model, we chose to base our research on previous work done in NLR over the same subject [37]. The risk model developed previously in [37] was profoundly extended, by adding new agents and by extending the current ones. As a result, we developed a new, significantly more complex model, which could serve our objectives, namely the reliable and realistic estimation of the fuel-exhaustion events. More specifically, the model was extended by adding eight new agents and by including hazards (the old model did not include hazards). Moreover, apart from our deep changes and developments in the risk model, we followed and implemented all the recommendations of [37]; the recommendations included the creation a more sophisticated weather model, the inclusion of more hazards and agents (especially an Air Traffic Controller agent), the implementation of a complex Flight Crew decision-making, the improvement of the routing model, and the considerations of several types of aircraft and routes (instead of one). After these additions in the model, we coped with difficulties faced by the previous work, and we finally managed to come up with useful estimations.

Next, in Chapter 4, a high-level description of the developed agent-based risk model is presented, along with the implementation characteristics (in Java) and the acceleration method. In specific, a total of 13 agent and non-agent entities are included in the model. Chapter 4 also includes the verification and validation processes of our model. Concerning the acceleration method, we implemented and employed the IPS method, a method which has already been used in the field by other researchers, as described in 4.3.

Finally, Chapter 5 includes the safety risk assessment part of our research (last steps of TOPAZ method). We evaluated the three main scenarios and we conduct the sensitivity analysis for scenario 1. We assessed all the scenarios, concluding that all scenarios are either acceptable or tolerable risk. It is of utmost importance to mention that no scenario was assessed as intolerable. At the end of this chapter we also identified and analyzed the bottlenecks that led to the fuel events. This analysis led us to identify the most important factors, which are: non-declaration of an emergency, increased fuel consumption both due to engine or aerodynamic degradation, landing gear malfunction, airport or weather delays and airspace avoidance. It is of importance to mention that no safety trends were identified regarding the aircraft type.

Being based on the results of this project, we may also indicate some “lessons learned” in the field of aircraft fuel planning and management. In the part of fuel planning, we saw that the applicable ICAO and European regulations stand sufficient in the direction of achieving the safety targets, as they were described in Chapter 2. In our simulations, the responsible for fuel planning agents, Flight Crew (Planning) and Dispatch, have not been identified to be the root cause of fuel events; this confirmed that fuel planning does not lack in safety. In the end, bad fuel planning could be mitigated through good fuel management (e.g. diversion to alternate). In the part of fuel management, we identified underlying safety risks, as identified in the bottlenecks section. In most of the cases, Flight Crew tried to solve the problem by diverting, if this was possible. Human performance was identified to be a root cause for fuel management events, with violations (e.g. non-declaration of an emergency) or non-diversions. Holdings due to bad weather or other operational reasons also contribute to fuel-related events in medium-range flights, as in many cases Flight Crew did not successfully cope with the solution of the issue. This was not the case for long-haul flights, because the flight crew had plenty of time and fuel to decide over deviations, far before arriving at the destination airport.

We conclude with recommendations for future work. Firstly, future research of the subject could include the examination of even more scenarios we finally did not simulate, such as Reduced Contingency Fuel procedures and flights into isolated aerodromes. Concerning the agents, it is recommended that the Air Traffic Control agent is further extended, creating different agent entities per phase of flight. This would lead to a more realistic simulation of reality. Moreover, we recommend the inclusion of even more ATCo and Flight Crew related hazards, as presented in the hazards list appendices, for possible identification of new safety risks. Finally, a sensitivity analysis for the delays' hazards occurrence frequency and duration would be recommended, in the direction of exploring the impact of the future delays (e.g. as described in Eurocontrol Network Performance), as well as the further expansion of the ETOPS scenarios (considering engine failures and cabin decompressions).

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Safety Risk Assessment in Aircraft Fuel Planning and Management

APPENDICES A-D

Appendix A Initial Hazards List

Table 44 Initial Hazards list [37]

ID	Description of hazard
H001	Tropical storm, winter storm, tornado, cyclone
H002	Icing, freezing precipitation, snow
H003	Heavy rain
H004	Strong winds
H005	Thunderstorms
H006	Wind shear
H007	Fog
H008	Dust or sandstorms
H009	Lightning
H010	Volcanic eruption
H011	Geophysical event on the ground, e.g. earthquake or tsunami
H012	Space weather (e.g. solar activity variations) affecting satellite communication or navigation
H013	ATM congestion
H014	Mechanical failure of an aeroplane system
H015	Adverse terrain or large bodies of water along the route
H016	Isolated aerodrome
H017	Runway closure
H018	Airspace closure
H019	Political unrest or terrorism
H020	Organization changes, e.g. changes to key personnel, rapid growth, rapid contraction, corporate mergers
H021	Operational changes, e.g. new equipment, adapted procedures
H022	Hazards affecting ATC capabilities
H023	Hazards affecting aerodromes
H024	Hazards affecting field condition reporting
H025	Hazards affecting meteorological reporting or forecasting
H026	Hazards affecting airline operational control, flight following and flight monitoring
H027	Longer taxi time than planned
H028	Taxi and ground delay
H029	En-route speed restriction
H030	En-route deviation
H031	Air traffic delay
H032	ATC flow management and aerodrome congestion
H033	Long time spent in holding

H034	Missed approaches
H035	Additional approaches
H036	Insufficient aircraft type-specific fuel planning experience of the flight crew
H037	Flight crew unfamiliar with the route
H038	Route near the maximum range of aeroplane
H039	Lack of routing accuracy of the flight management system
H041	Aircraft not equipped with technical system, e.g. auto-landing system
H042	Error in the routing of the flight management system, e.g. wrong waypoints in the database, or outdated FMS plan
H043	Airborne systems not working, e.g. cockpit display, flight management system, or large electronic failure
H044	Problem with instrument landing system
H045	Problem with landing gear
H046	Degradation of aircraft structure
H047	Problem with the positioning system, e.g. failure of GPS, navigation error in own position
H048	Degradation of one or multiple engines
H049	Problem with approach or runway lights
H050	Bird strike
H051	No ATC on an airport
H052	Runway blocked or contaminated
H053	Restricted airspace
H054	Complex standard arrival route
H055	The controller does not inform other controllers about an emergency situation
H056	Poor coordination between civil and military ATC
H057	Poor coordination between ATC centres
H058	Misidentification of an aircraft by ATC
H059	ATIS does not provide correct information to pilots
H060	Flight plans of the ATC system and FMS differ
H061	Malfunctioning of ATC systems, e.g. radar
H062	The controller makes a wrong decision
H063	The controller makes a mistake in aircraft identity
H064	VHF R/T communication is not working or delayed
H065	Poor R/T ability or poor knowledge of English, e.g. leading to misunderstanding by ATC of fuel problem
H066	Misunderstanding in communication between controller and pilot
H067	Wrong VHF R/T frequency selected
H068	The controller does not know whether an aircraft can fly a procedure
H069	Controller forgets aircraft
H070	The controller does not know the intent of an aircraft
H071	The controller does not know the aircraft’s position
H072	The controller does not know the availability of airspace infrastructure
H073	Controller is incapacitated

H074	Insufficient capacity of an ATC centre due to strike or illness
H075	The controller is not well trained to deal with an emergency situation
H076	Large workload of a controller
H077	Aircraft cannot perform requested manoeuvres, since it is over its performance limits
H078	Aircraft flies near its envelope extremes
H079	Aircraft is in a wrong mode for a particular action
H080	The pilot fails to obtain ATC authorization
H081	The pilot is not following the clearance because he tries to solve a problem
H082	Cockpit crew disagreement
H083	The pilot selects wrong route in the flight management system
H084	Pilots disconnect FMS
H085	The pilot does not know when to take action
H086	In an emergency procedure, aircraft may have to descend quickly and not have time to look out for other traffic
H087	Pilots cannot explain where they are, e.g. due to lack of waypoints
H088	Pilot validates without actually checking, e.g. fuel load
H089	Pilot makes an error in the calculation of the aircraft performance, e.g. aircraft weight, fuel quantity
H090	Alert causes attention tunnelling by pilots
H091	Difference in situation awareness of Pilot Flying and Pilot Not Flying
H092	Risk of fuel problem is underestimated by pilots
H093	Pilots receive wrong information about fuel quantity
H094	Pilots misinterpret information about fuel quantity
H095	Pilots are flying to the wrong airport
H096	Procedures and routes in TMA or at the airport are not well known by pilots (e.g. because pilots enter it seldom)
H097	Pilots (intend to) use wrong runway
H098	Aircrew unaware of the loss of voice communication
H099	The pilot does not detect degradation of an airborne system
H100	Delay into the detection of a problem by pilots due to lack of trust in a technical system
H101	Over-reliance of pilots on wrong system data
H102	Cultural differences impact the performance of crews
H103	Lack of situation awareness of pilot due to a high level of automation
H104	Pilot incapacitation
H105	Airline with a poor safety culture
H106	Pilot insufficiently trained for dealing with fuel management
H107	Large workload of the crew
H108	A pilot may lose interest when flight information updates (e.g. ATIS) are uploaded too frequently
H109	Changes or differences in procedures lead to confusion by pilots or controllers
H110	The occurrence of a situation which is not procedurally covered
H111	Difficult emergency procedures, leading to incorrect or late crew actions

H112	Wrong design of a procedure
H113	Rapid descent due to an aircraft system failure
H114	Avoiding bad weather leads to higher traffic density
H115	High traffic density
H116	Darkness
H117	Avoiding bad weather leads to an increase in crew workload and/or to a shift in pilot attention
H118	Weather influences the functioning of airborne systems
H119	Strong turbulence
H120	Pilot perception of weather areas may differ from info received
H121	Weather forecast wrong
H122	Sudden weather change disturbs planning
H123	Aircraft reacts on meteorological conditions that are not known to ATC
H124	Weather info not available
H125	Wind influences the expected time of arrival
H126	Overshoot of planned route due to wind
H127	Different wind speeds at different heights (vertical wind shear)
H128	Strong variation in wind
H129	Winter conditions at the airport
H130	Jet stream
H131	Mountain waves
H132	Significant temperature inversions
H133	Bird hazards and strikes
H134	Pilots feel pressed by management to reduce fuel intake
H135	Pilots plan a nearby alternate destination, which is in practice not a feasible option (e.g. for political reasons)
H136	Fuel quantity indicator is malfunctioning
H137	Pilots do not check fuel quantity
H138	Failure in the fuel system such that part of the fuel cannot be used
H139	Fuel leakage
H140	The crew does not follow the applicable procedures correctly
H141	Pre-flight maintenance error
H142	Fuel management not working properly, e.g. automatic transfer of fuel
H143	Inadequate certification requirements
H144	Fuel imbalance
H145	Fuel freezing
H146	Electrical failure
H147	Inability to fully retract flaps after a missed approach
H148	The aeroplane is flying in lower altitude than expected
H149	The pilot is not flying in optimal mode
H150	Malfunctioning of AOC systems
H151	Incorrect fuel bias

Appendix B Hazards List (before clustering)

Hazards Identified		
Crew rely on wrong system data	Fuel system failure (e.g., pump failure)	Noise abatement or weather avoidance radar vectoring
Error in the calculation of the aeroplane's performance	Automatic fuel transfer failure	Low-efficiency sequence radar vectoring
Alternate airport selection is inappropriate	Fuel imbalance	ATCO Industrial action (sudden)
The crew do not check fuel quantity before-flight	Fuel freezing	ATCO not in his/her position
The crew do not monitor fuel during flight	Ice accumulation in the fuel system	Staff shortages
The crew don't follow immediately ATC clearance	Fuel indication is wrong	Misidentification of an aeroplane
Crew fails to obtain ATC authorization	Fuel quantity/flow sensor is malfunctioning	ATCO lacks training
Crew rely on wrong system data	Poor Fuel quality/fuel contamination	ATCO makes wrong decisions – poor performance
Delays due to drones operations	Unwanted fuel jettison	ATCO not aware if an aeroplane can fly a procedure
Delay due to no-show passenger	Fuel leak	Poor R/T skills lead to misunderstanding in RT between ATC and pilots
Delay due to dispatching mistake	Erroneous input in FMS (Cost Index, wrong fix, consumption factor, flight's/aircraft's data)	ATCO is not aware of the airspace availability
Staff shortages	Aircraft's centre of gravity not optimum	ATCO forgets an aeroplane
Runway incursion	FMS database out of date	ATCO incapacitated
Airport closed	Flight Plan differs between FMS (ACARS downloaded) and ATC	Heavy workload
Lighting	Aircraft is in a wrong FMS mode (e.g. step descent vs approach)	Operational procedures change lead to confusion between pilots and ATC
Low visibility, fog or mist	Lack of routing accuracy	ATCO is not aware of the

		aeroplanes intentions
Tailwind over limit	Landing gear not retracting	Poor ATCO briefing during shift changes
Space weather	Landing gear not extending	Low situation awareness
Ground geophysical event (Earthquake or tsunami)	Flat tire(s)	NOTAM concerning airspace restriction not published or mistaken
Longer taxi length/time	Engine failure	NOTAM concerning airport restrictions or procedures changes or infrastructure changes not published or mistaken
Gate delay (CTOT, personnel)	Degraded engines	Central Flow Management Unit breakdown
Approach delay	Excessive APU usage	ATIS not correct or out of date
Departure delay	Degraded APU	VHF R/T communication not working
Congestion during approach	Damaged structure	Primary/secondary (en-route) surveillance radars failure
Delays due to the emergency of other traffic	Degraded structure	Weather info not available or not accurate during the planning
Delays due to weather	Ice formation on the structure	Dispatchers not aware of NOTAMs
Delays due to Security event	Structure is dirty	Dispatcher provides false flight data to the crew
Runway inspection/bird control	GPS failure	Dispatchers don’t account for higher consumption caused by aircraft degradation
No detection of a problem	INS/DME/VOR receivers failure	Dispatchers don’t account for higher consumption due to not ISA conditions
Automation leads to bad SA	VOR/ILS receivers/airborne system failure	Dispatchers overload aeroplane
Difference in SA between crew	VHF R/T failure/ LOST COMS	Dispatchers not aware of the exact passenger and cargo load
Crew unaware of VHF RT loss	ADS-B/transponder failure, identification turns	Fuel estimated not for the correct landing or take-off

		runway (runway change)
Poor spatial awareness	Jamming in CNS systems	No alternate fuel is dispatched
Insufficient fuel planning by the crew	Flaps retraction failure after Go Around	Incorrect fuel planning by dispatchers
Inadequate flight preparation/briefing	Flaps extension failure	Malfunction of AOC systems
Crew fly to the wrong airport	Control surfaces failure	AOC provides false information to pilots
Crew inserts wrong values (weights, fuel, consumption factor, CI, other parameters) in FMS	Partial electrical failure	Airline with a poor safety culture
Pilot disconnects FMS	Total electrical failure	Airline promotes unsafe fuel efficiency measures
Wrong route selection in FMS	Autopilot failure	Wrong design or lack of procedures
Pilot validates without checking	Ram air turbine extended	Weather info not available or not accurate during the planning
Alert causes attention fixation	wing anti-Ice failure	Dispatchers not aware of NOTAMs
Crew intend to use the wrong runway	Engine anti-Ice failure	Dispatcher provides false flight data to the crew
Runway blocked	Bleed Air system failure	Dispatchers don’t account for higher consumption caused by aircraft degradation
The aeroplane flies under MEL, affecting fuel consumption but the crew do not consider the extra consumption	Storm	Dispatchers don’t account for higher consumption due to not ISA conditions
The aeroplane flies under CDL (Configuration Deviation List), affecting fuel consumption but the crew do not consider the extra consumption	Wind variation	Dispatchers overload aeroplane
Non stabilized approach	Jet stream variation	Dispatchers not aware of the exact passenger and cargo load
Wrong VHF R/T frequency selected	Wind shear (high level)	Fuel estimated not for the correct landing or take-off runway (runway change)

Crew fatigue	Heavy rain	No alternate fuel is dispatched
Crew suffer from startle effect	Thunderstorm	Incorrect fuel planning by dispatchers
Crew low performance	Turbulence, Clear Air Turbulence	Malfunction of AOC systems
The crew doesn't ask for extra fuel	Freezing rain, freezing snow	AOC provides false information to pilots
Crew unfamiliar with the route	Snow	Airline with a poor safety culture
Crew poor R/T skills	Icing Conditions	Airline promotes unsafe fuel efficiency measures
Bad CRM performance	Other atmospheric parameters difference (temperature, humidity)	Wrong design or lack of procedures
The crew is unfamiliar with procedures in a TMA or at an airport	Airspace closure	Wrong forecast
Crew disagreement	Airspace restricted	Lack of forecast means
The crew doesn't follow the company's procedures	Dangerous Airspace	Low-quality forecast methods
Misunderstanding between ATCo and pilot	Reduced airspace capacity	Weather cannot be forecasted by existing methods
Crew not aware of NOTAMs	ATM congestion	Flawed spare part
ILS or VOR system failure	Bad weather avoidance leads to congestion	Design mistake
Runway contaminated	Drones operations	Instance not covered in Flight Crew Operations Manual (FCOM)
Primary/secondary surveillance radars failure	Uncontrolled re-entry of satellites	Instance not covered in Maintenance Manual
ATCO uses a different flight plan than the pilots	Armed conflicts	Flawed spare part
ATCO doesn't know aeroplane's position	Volcanic eruption	Design mistake
Poor coordination between ATCO of different centres	Hurricanes	Instance not covered in Flight Crew Operations Manual (FCOM)
Poor coordination between civil/military ATC	Space weather (e.g. Solar activity)	Instance not covered in Maintenance Manual
Competent authority Audit/inspections not sufficient	Wind shear (low level)	Maintenance error
Lack of safety culture of the	Mountain Waves	Spare part erroneously placed

competent authority		
The cabin is not secure. Cabin crew provoke landing delay (e.g. unfinished services by cabin crew, unruly passenger)	Icing Conditions	Low-quality maintenance procedures
Incorrect fuel load by Ground Handler	Hail or ice pellets	Lack of safety culture
Delay the departure (before engines start)	Dust or sand storm	Airline Personnel lack of Training or experience
Identified anomaly is not notified/reported by Ground Handler	Heavy rain	Unsafe cost-saving practices
Ground Handler damages the aeroplane	Thunderstorm	Maintenance schedule not followed
Insufficient de-ice by Ground Handler	Turbulence	Weather information not available
Safety culture, training or experience lack of Ground Handler	Freezing rain, freezing snow	The crew receive wrong info about fuel quantity loaded
Crew not aware of operational changes	Snowfall (heavy)	Crew misinterpret info about fuel quantity
Crew concentrate on troubleshooting or briefing procedures, provoking (nav) delays		

Appendix C Hazards List (after clustering)

Table 45 Aircraft (AC) related hazards

Category	Hazard ID	Hazard description	Used in
Fuel System	H01	Fuel system failure (e.g., pump failure)	AC_HG_5
	H02	Automatic fuel transfer failure	AC_HG_5
	H03	Fuel imbalance	AC_HG_5
	H04	Fuel freezing	AC_HG_5
	H05	Ice accumulation in the fuel system	AC_HG_5
	H06	Fuel indication is wrong	
	H07	Fuel quantity/flow sensor is malfunctioning	
	H08	Poor Fuel quality/fuel contamination	AC_HG_5
	H09	Unwanted fuel jettison	
	H10	Fuel leak	AC_HG_6
Flight Management System (FMS) and Optimality	H11	Erroneous input in FMS (Cost Index, wrong fix, consumption factor, flight’s/aircraft’s data)	
	H12	Aircraft’s centre of gravity not optimum	AC_HG_5
	H13	FMS database out of date	
	H14	Flight Plan differs between FMS (ACARS downloaded) and ATC	
	H15	Aircraft is in a wrong FMS mode (e.g. step descent vs approach)	
	H16	Lack of routing accuracy	
Landing Gear/ Tires	H17	Landing gear not retracting	AC_HG_2
	H18	Landing gear not extending	AC_HG_2
	H19	Flat tire(s)	
Propulsion and APU	H20	Engine failure	
	H21	Degraded engines	AC_HG_1
	H22	Excessive APU usage	
	H23	Degraded APU	
Structure	H24	Damaged structure	AC_HG_3
	H25	Degraded structure	AC_HG_3, AC_HG_4
	H26	Ice formation on the structure	AC_HG_4
	H27	Structure is dirty	AC_HG_3
Communication, Navigation	H28	GPS failure	
	H29	INS/DME/VOR receivers failure	
	H30	VOR/ILS receivers/airborne system failure	

and Surveillance (CNS)	H31	VHF R/T failure/ LOST COMS	
	H32	ADS-B/transponder failure, identification turns	
	H33	Jamming in CNS systems	
Flight Controls/ Hydraulics	H34	Flaps retraction failure after Go Around	
	H35	Flaps extension failure	
	H36	Control surfaces failure	
Avionics, Instruments and Electrics	H37	Partial electrical failure	
	H38	Total electrical failure	
	H39	Autopilot failure	
	H40	Ram air turbine extended	
Bleed Air	H41	wing anti-Ice failure	
	H42	Engine anti-Ice failure	
	H43	Bleed Air system failure	

Table 46 Environment (EN) Hazards

Category	Hazard ID	Hazard description	Used in
Weather	H44	Storm	EN HG1
	H45	Wind variation	
	H46	Jet stream variation	
	H47	Wind shear (high level)	EN HG1
	H48	Heavy rain	
	H49	Thunderstorm	EN HG1
	H50	Turbulence, Clear Air Turbulence	EN HG1
	H51	Freezing rain, freezing snow	EN HG1
	H52	Snow	EN HG1
	H53	Icing Conditions	EN HG1
	H54	Other atmospheric parameters difference (temperature, humidity)	
Airspace and Terrain	H55	Airspace closure	
	H56	Airspace restricted	
	H57	Dangerous Airspace	
	H58	Reduced airspace capacity	
	H59	ATM congestion	
	H60	Bad weather avoidance leads to congestion	
	H61	Drones operations	EN HG3
	H62	Uncontrolled re-entry of satellites	EN HG2
	H63	Armed conflicts	EN HG3

Natural phenomena	H64	Volcanic eruption	EN HG3
	H65	Hurricanes	EN HG3
	H66	Space weather (e.g. Solar activity)	EN HG2

Table 1 Airport (AP) related hazards

Category	Hazard ID	Hazard description	Used in
Airport weather and natural phenomena	H67	Wind shear (low level)	AP_HZ_G3
	H68	Mountain Waves	AP_HZ_G3
	H69	Icing Conditions	
	H70	Hail or ice pellets	
	H71	Dust or sand storm	
	H72	Heavy rain	
	H73	Thunderstorm	
	H74	Turbulence	
	H75	Freezing rain, freezing snow	
	H76	Snowfall (heavy)	
	H77	Lighting	
	H78	Low visibility, fog or mist	
	H79	Tailwind over limit	AP_HZ_G3
	H80	Space weather	
	H65	Ground geophysical event (Earthquake or tsunami)	
Operational delays and events	H81	Longer taxi length/time	
	H82	Gate delay (CTOT, personnel)	AP_HZ_G6
	H83	Approach delay	
	H84	Departure delay	
	H85	Congestion during approach	AP_HZ_G1
	H86	Delays due to emergency of other traffic	AP_HZ_G1, AP_HZ_G6
	H87	Delays due to weather	
	H88	Delays due to Security event	AP_HZ_G4
	H89	Delays due to drones operations	AP_HZ_G4
	H90	Delay due to no-show passenger	AP_HZ_G6
	H91	Delay due to dispatching mistake	
	H92	Staff shortages	
	H93	Runway incursion	AP_HZ_G2
Infrastructure	H94	Airport closed	
	H95	Runway blocked	
	H96	Runway inspection/bird control	AP_HZ_G2, AP_HZ_G5

	H97	ILS or VOR system failure	AP_HZ_G1
	H98	Runway contaminated	AP_HZ_G2, AP_HZ_G5
	H99	Primary/secondary surveillance radars failure	AP_HZ_G1

Table 47 Air Traffic Controller (ATCo) related hazards

Category	Hazard ID	Hazard description	Used in
Operations	H100	ATCO uses a different flight plan than the pilots	
	H101	ATCO doesn’t know aeroplane’s position	
	H102	Poor coordination between ATCO of different centres	
	H103	Poor coordination between civil/military ATC	
	H104	Noise abatement or weather avoidance radar vectoring	
	H105	Low-efficiency sequence radar vectoring	ATCO_HG1
	H106	ATCO Industrial action (sudden)	ATCO_HG2
	H107	ATCO not in his/her position	ATCO_HG2
	H108	Staff shortages	
Situation Awareness, human limitations and mistakes	H109	Misidentification of an aeroplane	
	H110	ATCO lacks training	
	H111	ATCO makes wrong decisions – poor performance	
	H112	ATCO not aware if an aeroplane can fly a procedure	
	H113	Poor R/T skills lead to misunderstanding in RT between ATC and pilots	
	H114	ATCO is not aware of the airspace availability	ATCO_HG1
	H115	ATCO forgets an aeroplane	ATCO_HG1
	H116	ATCO incapacitated	
	H117	Heavy workload	
	H118	Operational procedures change lead to confusion between pilots and ATC	
	H119	ATCO is not aware of the aeroplanes intentions	
	H120	Poor ATCO briefing during shift changes	
	H121	Low situation awareness	
NOTAM officers	H122	NOTAM concerning airspace restriction not published or mistaken	
	H123	NOTAM concerning airport restrictions or procedures changes or infrastructure changes	

		not published or mistaken	

Table 48 ATC system (ATCS) related hazards

Category	Hazard ID	Hazard description	Used in
ATC systems	H124	Central Flow Management Unit breakdown	
	H125	ATIS not correct or out of date	
	H126	VHF R/T communication not working	
	H127	Primary/secondary (en-route) surveillance radars failure	ATCS

Table 49 Airline’s Dispatch (AD) related hazards

Category	Hazard ID	Hazard description	Used in
Dispatching	H128	Weather info not available or not accurate during the planning	
	H129	Dispatchers not aware of NOTAMs	
	H130	Dispatcher provides false flight data to the crew	
	H131	Dispatchers don’t account for higher consumption caused by aircraft degradation	
	H132	Dispatchers don’t account for higher consumption due to not ISA conditions	
	H133	Dispatchers overload aeroplane	
	H134	Dispatchers not aware of the exact passenger and cargo load	
	H135	Fuel estimated not for the correct landing or take-off runway (runway change)	
	H136	No alternate fuel is dispatched	
	H137	Incorrect fuel planning by dispatchers	
Operations Centre (AOC)	H138	Malfunction of AOC systems	
	H139	AOC provides false information to pilots	
Policy and procedures	H140	Airline with a poor safety culture	
	H141	Airline promotes unsafe fuel efficiency measures	
	H142	Wrong design or lack of procedures	

Table 50 Meteorological Service (MET) related hazards

Category	Hazard	Hazard description	Used in

	ID		
Weather forecast	H143	Wrong forecast	MET
	H144	Lack of forecast means	
	H145	Low-quality forecast methods	
	H146	Weather cannot be forecasted by existing methods	

Table 51 Aircraft manufacturer related hazards

Category	Hazard ID	Hazard description	Used in
Aircraft manufacture	H147	Flawed spare part	
	H148	Design mistake	
	H149	Instance not covered in Flight Crew Operations Manual (FCOM)	
	H150	Instance not covered in Maintenance Manual	

Table 52 MRO related hazards

Category	Hazard ID	Hazard description	Used in
Human factors, culture and procedures	H151	Maintenance error	MRO
	H152	Spare part erroneously placed	
	H153	Low-quality maintenance procedures	
	H154	Lack of safety culture	
	H155	Lack of Training or experience	
	H156	Unsafe cost-saving practices	
	H157	Maintenance schedule not followed	

Table 53 Flight Crew (FC) related Hazards

Category	Hazard ID	Hazard description	Used in
Human mistakes	H158	Insufficient fuel planning by the crew	FC_PL
	H159	Inadequate flight preparation/briefing	
	H160	Crew fly to the wrong airport	
	H161	Crew inserts wrong values (weights, fuel, consumption factor, CI, other parameters) in FMS	
	H162	Pilot disconnects FMS	
	H163	Wrong route selection in FMS	

	H164	Pilot validates without checking	
	H165	Alert causes attention fixation	
	H166	Crew concentrate on troubleshooting or briefing procedures, provoking (nav) delays	
	H167	Crew intend to use the wrong runway	
	H168	Crew rely on wrong system data	
	H169	Error in the calculation of the aeroplane's performance	
	H170	Alternate airport selection is inappropriate	
	H171	The crew do not check fuel quantity before-flight	FC_PL
	H172	The crew do not monitor fuel during flight	FC_SA
	H173	The crew don't follow immediately ATC clearance	
	H174	Crew fails to obtain ATC authorization	
	H177	The aeroplane flies under MEL, affecting fuel consumption but the crew do not consider the extra consumption	FC_PL
	H178	Aeroplane flies under CDL (Configuration Deviation List) ,affecting fuel consumption but crew do not consider the extra consumption*	FC_PL
	H179	Non stabilized approach	
	H180	Wrong VHF R/T frequency selected	
Human limitations	H181	Crew fatigue	
	H182	Crew suffer from startle effect	
	H183	Crew low performance	
Experience/ Training/ Culture	H184	The crew doesn't ask for extra fuel	FC_PL
	H185	Crew unfamiliar with the route	
	H186	Crew poor R/T skills	
	H187	Bad CRM performance	
	H188	The crew is unfamiliar with procedures in a TMA or at an airport	
	H189	Crew disagreement	
	H190	The crew doesn't follow the company's procedures	
Situation awareness	H191	Misunderstanding between ATC and pilot	
	H192	Crew not aware of NOTAMs	
	H193	Crew not aware of operational changes	
	H194	The crew don't detect degradation of systems	

	H195	Weather information not available	
	H196	The crew receive wrong info about fuel quantity loaded	FC_PL
	H197	Crew misinterpret info about fuel quantity	
	H198	No detection of a problem	
	H199	Automation leads to bad SA	
	H200	Difference in SA between crew members	
	H201	Crew unaware of VHF RT loss	
	H202	Poor spatial awareness	

Table 54 Cabin Crew (CC) related hazards

Category	Hazard ID	Hazard description	Used in
Cabin Crew	H203	The cabin is not secure. Cabin crew provoke landing delay (e.g. unfinished services by cabin crew, unruly passenger)	CC

Table 55 Ground Handling (GH) related hazards

Category	Hazard ID	Hazard description	Used in
Human factors, culture and procedures	H204	Incorrect fuel load	GH
	H205	Delay the departure (before engines start)	GH
	H206	Identified anomaly not notified/reported	
	H207	GH damages the aeroplane	
	H208	Insufficient de-ice	
	H209	Safety culture, training or experience lack	

Table 56 Oversight authority related hazards

Category	Hazard ID	Hazard description	Used in
Audits	H210	Audit/inspections not sufficient	
	H211	Lack of safety culture	

Appendix D SDCPN Model Specifications

In this Appendix, we will present the description of Stochastic Dynamically Coloured Petri Nets (SDCPN) model.

D.1 Probability distributions and delay functions distributed time values calculations

The means of exponentially distributed time values τ that are used in modelling delay transitions are calculated as shown in Table 57.

Table 57 Exponentially distributed time function used for modelling delay transitions

Transition	Function	Distribution type	Source
nominal → non-nominal	$\tau \leftarrow f_E(\mu_{non} \frac{1-p_{non}}{p_{non}})$	Exponential	[48]
non-nominal → nominal	$\tau \leftarrow f_E(\mu_{non})$	Exponential	[48]

The distributions used in the modelling are the Normal $N(\mu,\sigma)$, the Normal truncated $N_t(\mu,\sigma,l,u)$, the Uniform U and the Exponential f_E. The functions of each distribution are demonstrated below.

Table 58 Functions used in the model

Function and notation	Distribution type
$f_E(x;\lambda) = \begin{cases} \lambda \exp(-\lambda x) & x \geq 0 \\ 0 & x < 0 \end{cases}$	Exponential
$N(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp(-\frac{(x-\mu)^2}{2\sigma^2})t$	Normal
$N_t(x;\mu,\sigma,l,u) = \frac{N(\xi)}{\sigma Z}, where:$ $\xi = \frac{x-\mu}{\sigma}, l = \frac{\alpha-\mu}{\sigma}, u = \frac{x-\mu}{\sigma}$ $Z = \Phi(u) - \Phi(l)$ $\Phi = \frac{1}{2}(1 + erf\,\frac{x}{\sqrt{2}})$	Normal Truncated
$U(x;a,b) = \begin{pmatrix} \frac{1}{b-a} & , x \in [a,b] \\ 0\ ,otherwise & \end{pmatrix}$	Uniform

D.2 Local Petri Nets Names

Acronym	Name	Acronym	Name	Acronym	Name
AC_CH	Aircraft Characteristics	AP_CH	Airport Characteristics	ATCO_SA	Air Traffic Controller Situational Awareness
AC_FS	Aircraft Fuel System	AP_WX	Airport Weather	ATCO_AC	Air Traffic Controller Actions
AC_HZ	Aircraft Hazards	AP_HZ_1	Airport Hazards group 1	ATCS	Air Traffic Control System
AC_IC	Aircraft Icing	AP_HZ_2	Airport Hazards group 2	ATCO_HZ_1	Air Traffic Controller Hazards group 1
AC_ST	Aircraft State	AP_HZ_3	Airport Hazards group 3	ATCO_HZ_2	Air Traffic Controller Hazards group 2
AD	Airlines Dispatch	AP_HZ_4	Airport Hazards group 4	EN_CH	Environment Characteristics
CC	Cabin Crew	AP_HZ_5	Airport Hazards group 5	EN_HZ_1	Environment Hazards group 1
FMS	Flight Management System	AP_HZ_6	Airport Hazards group 6	EN_HZ_2	Environment Hazards group 2
MET	Meteorological Service	NOTAM	NOTAM office	EN_HZ_3	Environment Hazards group 3
FC_PL	Flight Crew Planning	FC_EV	Flight Crew Evolution	MRO	Maintenance Repair and Overhaul
FC_SA	Flight Crew Situational Awareness	FC_AC	Flight Crew Actions	GH	Ground Handler

D.3 Environment (EN)

Assumptions

1. Considering the sectors availability, “true” denotes that the sector is available.
2. Weather changes for each medium-sized sector (S_2).
3. At time point t=0, the wind speed and direction matrices are created for every sector as follows: First, random wind speed and direction is assigned for the sector (0, 0) at reference altitude. Then, the wind characteristics for the rest of the sectors are created as a function of the sector (0, 0), for reference altitude. This function is a small deviation (or no deviation) added or subtracted randomly, at each adjacent sector. In this way, the wind all over the environment will change for each sector randomly and smoothly, in comparison with the adjacent sectors.
4. After creating the wind characteristics for all sectors at t=0 at reference altitude, adding or subtracting a small deviation (or no deviation) from the initial value (t=0), we create the

wind characteristics for all time points for the reference altitude. As a result, there is a smooth transition for the wind characteristics for all time points, for the same sector.

5. The calculation of the wind characteristics for all altitudes, starting with a reference altitude, is based on the atmosphere model provided in [Eurocontrol Experimental Centre, 2011]
6. Considering the three environment hazards groups, at each time period, any of the hazards may be triggered. The hazard triggering moment follows an exponential distribution, modelled by the Petri-nets delay functions. When the corresponding delay function triggers, the hazard covers a random but predetermined in size, part of the airspace.
7. The model considers as environment only a part of the real environment's size (entire planet) to save computational power.

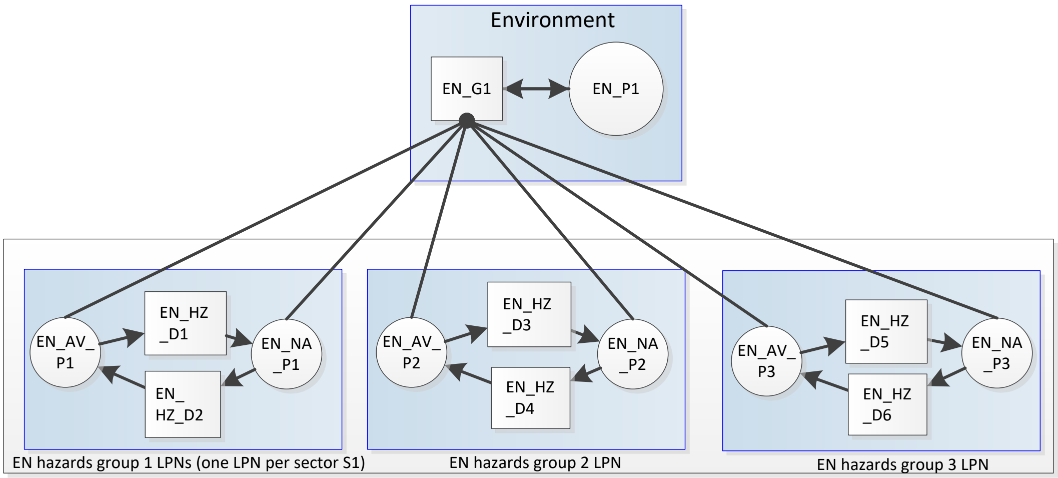

Figure 24 Environment Local Petri Net and interactions

Table 59 Environment hazards group 1(weather): hazards grouping and characteristics

Hazards group number	Hazards' serial numbers	Event description	Airspace closure size
HG1	H44, H49, H50(H47), H51(H52, H53)	(Thunder)storm, Turbulence (wind shear), Icing conditions (freezing Rain/snow)	Sector S_1

Table 60 EN hazards groups 2 and 3 (airspace closure): hazards grouping and characteristics

Hazards group number	Hazards' serial numbers	Event description	Airspace closure size
HG 2	H62, H66	Airspace closures re-entry of a satellite (controlled/uncontrolled) or space debris, Space weather	Sector S_2

HG 3	H63(H61), H64, H65	Armed Conflict-military manned and unmanned operations, Volcanic Eruption, Hurricane	Sector S_3

Environment LPN

Colour type

Colour type	Notation	State Space	Description
EN	$w_{EN}^{n_2,m_2,t,h}$	$\mathbb{R}$	Wind speed for all sectors S_2, for all time periods $t \in T$, and for all altitudes layers $h \in H$.
	$\varphi_{EN}^{n_2,m_2,t,h}$	$[0,2\pi]$	The direction of the wind for all sectors S_2, for all time periods $t \in T$, and for all altitudes layers $h \in H$.
	$\begin{pmatrix} w_{x,EN}^{n_2,m_2,t,h} \\ w_{y,EN}^{n_2,m_2,t,h} \end{pmatrix}$	$\mathbb{R}^2$	Wind speed components on the longitudinal (x) and lateral (y) axis, for all sectors S_2, for all time periods $t \in T$, and for all altitudes layers $h \in H$.
	$A_{1EN}^{n_1,m_1,t}$	$\{true,\ false\}$	The current situation of the airspace at small sector level due to weather (true means available)
	$A_{2EN}^{n_1,m_1,t}$	$\{true,\ false\}$	The current situation of the airspace at medium sector level (true means available) (excluding weather)
	$A_{3EN}^{n_1,m_1,t}$	$\{true,\ false\}$	The current situation of the airspace at large sector level (true means available) (excluding weather)
	t_{EN}^{G1}	$\mathbb{R}$	Timer for guard transition G1

Colour function

Place	Colour type	Colour function
EN_P1	EN	$dt_{EN}^{G1} = -dt$

Initial marking

Place	Initial Colour
EN_P1	A token with colour EN: $w_{EN}^{0,0,0,0} \sim N_t\left(\mu_w, \sigma_w, w_{min}, w_{max}\right)$ $\varphi_{EN}^{0,0,0,0} \sim Un\left(0, 2\pi\right)$ $\forall n_2 \in N, \forall m_2 \in M, \forall t \in T$ $w_{EN}^{n_2,m_2,0,0} = w_{EN}^{n_2-1,m_2-1,0,0} + N(\mu_w^{EN}, \sigma_w^{EN})$ $\varphi_{EN}^{n_2,m_2,0,0} = \varphi_{EN}^{n_2-1,m_2-1,0,0} + N(\mu_\varphi^{EN}, \sigma_\varphi^{EN})$

	$\forall n_2 \in N, \forall m_2 \in M, \forall t \in T$ $w_{EN}^{n_2,m_2,t,0} = w_{EN}^{n_2,m_2,t-1,0} + N(\mu_{w2}, \sigma_{w2})$ $\varphi_{EN}^{n_2,m_2,t,0} = \varphi_{EN}^{n_2,m_2,t-1,0} + N(\mu_{\varphi 2}, \sigma_{\varphi 2})$ $\forall n_1 \in N, \forall m_1 \in M, \forall t \in T$ $A_{EN}^{n_1,m_1,t} = true$ If $h \leq h_P$ $w_{EN}^{n_2,m_2,t,h} = \begin{pmatrix} w_x^{n_2,m_2,t,h} \\ w_y^{n_2,m_2,t,h} \end{pmatrix} = w_{EN}^{n_2,m_2,t,0} \cdot \dfrac{\ln(1+C_{w1}h)}{\ln(1+C_{w1}h_{ref})} \cdot \begin{pmatrix} \cos\varphi_{EN}^{n_2,m_2,t,0} \\ \sin\varphi_{EN}^{n_2,m_2,t,0} \end{pmatrix}$ If $h_P < h \leq h_E$ $w_{EN}^{n_2,m_2,t,h} = w_{EN}^{n_2,m_2,t,h_P} \cdot \left[1+(C_{w2}-1)\cdot\left(1-e^{-\frac{h-h_P}{D_E}}\right)\right]$ If $h > h_E$ $w_{EN}^{n_2,m_2,t,h} = C_{w2} \cdot w_{EN}^{n_2,m_2,t,h_P}$ $h_E = C_{w3} \cdot \dfrac{2\alpha}{(1-\alpha)^2} \cdot \dfrac{w_{EN}^{n_2,m_2,t,h}}{\ln(1+C_{w1}h_{ref})}$ $h_P = \alpha h_E$ $D_E = \sqrt{C_{w4}h_P \cdot \dfrac{w_{EN}^{n_2,m_2,t,h}}{\ln(1+C_{w1}h_{ref})}}$ $\rho(h) = \dfrac{p(h)}{R\tau(h)}$ Where: $\tau(h) = \begin{cases} \tau_0 + \beta h & \text{if} \quad h \leq h_{trop} \\ \tau_0 + \beta h_{trop} & \text{if} \quad h > h_{trop} \end{cases}$ $\tau_{trop} = \tau(h_{trop})$ $\tau(h) = \begin{cases} p_0 \cdot \left(\dfrac{\tau(h)}{\tau_0}\right)^{-\frac{g}{R\beta}} & \text{if} \quad h \leq h_{trop} \\ p_{trop} \cdot e^{\left[\frac{g}{R\tau_{trop}}\cdot(h_{trop}-h)\right]} & \text{if} \quad h > h_{trop} \end{cases}$ $p_{trop} = p(h_{trop})$

Guard transitions

Transition	Guard condition	Firing function

EN_G1: EN_AV_P1→EN_P1 EN_NA_P1→EN_P1 EN_AV_P2→EN_P1 EN_NA_P2→EN_P1 EN_AV_P3→EN_P1 EN_NA_P4→EN_P1	$t_{EN}^{G1} \leq 0$	A token with colour EN $\forall n_1 \in N_2, \forall m_2 \in M_2$ $\forall n_2 \in N_2, \forall m_2 \in M_2$ $\forall n_3 \in N_3, \forall m_3 \in M_3$ $\forall t \in T:$ $A_{1,EN}^{n_1,m_1,t} = S_1^{n_1,m_1,t}$ $A_{2,EN}^{n_2,m_2,t} = S_2^{n_2,m_2,t}$ $A_{3,EN}^{n_3,m_3,t} = S_3^{n_1,m_1,t}$ $t_{EN}^{G1} = \Delta t_{EN}^{G1}$

Parameters

Parameters	Description	Value	Explanation
N_1, M_1	number of rows and columns of square small sectors	$[160, 40]$	Based on sectors size S_1, to capture the appropriate size for operations understudy
N_2, M_2	number of rows and columns of square medium Sectors	$\frac{N_1}{f_1^{EN}}, \frac{M_1}{f_1^{EN}}$	Based on sectors size S_2 , chosen as appropriate for simulating wind changes and environment hazards of group 2
N_3, M_3	number of rows and columns of square large sectors	$\frac{N_1}{f_2^{EN}}, \frac{M_1}{f_2^{EN}}$	Based on sectors size S_3, chosen as appropriate for simulating hazards of group 3
$d_{\sec}^{S_1}$	Length of the S_1 (small sector) side	$80000\ m$	Typical size of a Terminal Manoeuvring Area (TMA)
$d_{\sec}^{S_2}$	Length of the S_2 (medium sector) side	$d_{\sec}^{S_1} \cdot f_1^{EN}\ m$	The size is chosen as a representative size of airspace that EN hazards group 2 triggering would occupy
$d_{\sec}^{S_3}$	Length of the S_3 (large sector) side	$d_{\sec}^{S_2} \cdot f_2^{EN}\ m$	The size is chosen as a representative size of airspace that EN hazards group 3 triggering would occupy
f_1^{EN}	Factor change between $d_{\text{sector}}^{S_1}$ and $d_{\text{sector}}^{S_2}$	5	Factor choice was based on the assumption of wind change in the sector S_2
f_2^{EN}	Factor change between $d_{\text{sector}}^{S_1}$ and $d_{\text{sector}}^{S_3}$	10	Factor choice was based on the assumption of the effect of environment group 3 hazards
t_{period}	The time period used in the creation of the environment	$900\ s$	The time division was chosen due to computational power needs

	characteristics (15min)		
T_{period}	Set of time periods	1: 40 2: 88	Based on the time needed for each type of operations 1. Intracontinental operations (10 hours) 2. Intercontinental operations (22 hours)
h_{step}	Altitude division of the airspace	$914\ m$	Division of height chosen due to computational power needs
H	Set of altitude sections (divisions)	14	The value is chosen based on the assumption that the maximum altitude of the environment is 12796m (~42000ft)
α	the quotient of the height of the Brandt layer and Ekman layer	0.025	*Chapter 3 of the User Manual for the Base of Aircraft Data (BADA) Revision 3.14.*
h_{ref}	reference altitude	$10\ m$	*Chapter 3 of the User Manual for the Base of Aircraft Data (BADA) Revision 3.14.*
C_{w1}	wind coefficient	$\frac{100}{3}\ m^{-1}$	*Chapter 3 of the User Manual for the Base of Aircraft Data (BADA) Revision 3.14.*
C_{w2}	wind coefficient	1.6732	*Chapter 3 of the User Manual for the Base of Aircraft Data (BADA) Revision 3.14.*
C_{w3}	wind coefficient	$12302\ s$	*Chapter 3 of the User Manual for the Base of Aircraft Data (BADA) Revision 3.14.*
C_{w4}	wind coefficient	$840.5\ s$	*Chapter 3 of the User Manual for the Base of Aircraft Data (BADA) Revision 3.14.*
h_{trop}	altitude at which the tropopause begins	$11000\ m$	*Chapter 3 of the User Manual for the Base of Aircraft Data (BADA) Revision 3.14.*
τ_0	the temperature at sea level	$288.15\ K$	*Chapter 3 of the User Manual for the Base of Aircraft Data (BADA) Revision 3.14.*
β	temperature gradient below the tropopause	$-0.0065\ K \cdot m^{-1}$	*Chapter 3 of the User Manual for the Base of Aircraft Data (BADA) Revision 3.14.*
p_0	the pressure at sea level	$101\,325\ Pa$	*Chapter 3 of the User Manual for the Base of Aircraft Data (BADA) Revision 3.14.*
g	gravitational acceleration	$9.80665\ m \cdot s^{-2}$	*Chapter 3 of the User Manual for the Base of Aircraft Data (BADA) Revision 3.14.*
R	real gas constant for air	$287.05287\ m^2 \cdot K^{-1} \cdot s^{-2}$	*Chapter 3 of the User Manual for the Base of Aircraft Data (BADA) Revision 3.14.*
μ_w, σ_w, w_{min}, w_{max}	Truncated normal distribution parameters	$5,1,2,8\ m \cdot s^{-1}$	Values are chosen following a light surface wind assumption

	of reference wind speed		
$\mu_w^{EN}, \sigma_w^{EN}$	Normal distribution parameters of the wind speed initialization	$w_{EN}^{n_2-1,m_2-1,0,0}$, $\frac{w_{EN}^{n_2-1,m_2-1,0,0}}{10}$ $m \cdot s^{-1}$	Based on the assumption that wind should smoothly change for adjacent sectors
$\mu_\varphi^{EN}, \sigma_\varphi^{EN}$	Normal distribution parameters of the wind direction initialization	$0, \frac{\pi}{25}$ rad	Based on the assumption that wind should smoothly change for adjacent sectors
Δt_{EN}^{G1}	Timer for guard transition G1	900 s	Minimum time parameter (one t_{period})

Incoming arcs within the same agent

There are incoming arcs from the (three) environment hazards groups LPNs.

Outgoing arcs within the same agent

None.

Incoming arcs from other agents

None.

Outgoing arcs to other agents

There are outgoing arcs to NOTAM, Met office, AC_FS, FMS and AC_ST.

- NOTAM uses the airspace information to publish the appropriate NOTAMS.
- Meteorological service office used the weather information to publish the weather forecast.
- FMS used wind speed information to calculate the ground speed of the aircraft.
- AC_ST uses environment information for position and airspeed.
- The fuel system uses parameters and information about air density required to compute fuel flow.

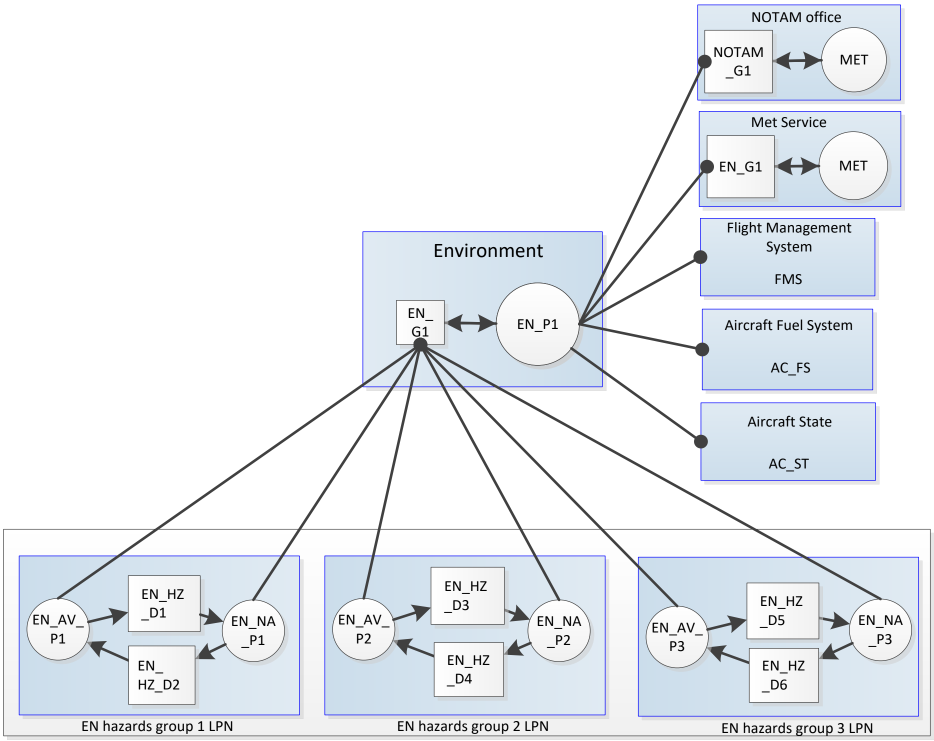

Figure 25 EN LPN with interactions

Environment’s hazards group 1 LPN

- Each Sector S_1 is modelled with an identical but separate LPN. Hence, there are $N_1 x M_1$ LPNs of this type, determining if the hazards group in the specific sector is triggered.
- EN_AV_P1: Sector S_1 is available.
- EN_NA_P1: Sector S_1 is not available due to hazards of group 1

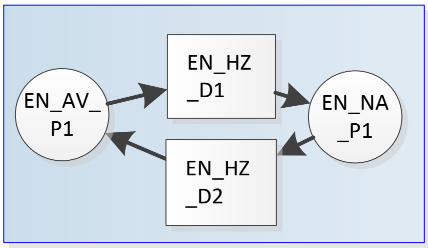

Figure 26 Environment's hazards LPN Hazards group 1

Colour type

Colour type	Notation	State Space	Description
EN_HZ_1	$S_1^{n_1,m_1,t}$	$\{\text{true},\ \text{false}\}$	Matrix of size $N_1 \cdot M_1$. Each sector $S_1^{n_1,m_1}$ may be available (true) or not available (false) due to the respective group hazards

Colour function

Place	**Colour type**	**Colour function**
EN_AV_P1	EN_HZ_1	constant
EN_NA_P1	EN_HZ_1	constant

Initial marking

Place	Initial Colour
EN_AV_P1	A token with colour EN_HZ_1 $\forall n_1 \in N_1, \forall m_1 \in M_1, \forall t \in T : S_1^{n_1,m_1,t} = true$ Parameter from other LPNs: • N_1, M_1 from EN

Delay transitions

Transition	Delay rate	Firing function
EN_HZ_D1: EN_AV_P1→ EN_NA_P1	Delay~ Exp($\Delta t_{EN\_HZ\_D1}$)	A token with colour EN_HZ_1: $n_1, m_1 \in [N_1, M_1]$: $S_1^{n_1,m_1,t} = false$ Parameters N_1, M_1 from EN LPN
EN_ HZ_D2: EN_NA_P1 → EN_AV_P1	Delay~ Exp($\Delta t_{EN\_HZ\_D2}$)	A token with colour EN_HZ_1 $n_1, m_1 \in [N_1, M_1]$: $S_1^{n_1,m_1,t} = true$ Parameters N_1, M_1 from EN LPN

Parameters

Parameters	**Description**	**Value**	**Explanation**
$p_{non}^{EN\_GH1}$	The probability that a token will be at the place EN_NA_P1	0.0005	H44: Based on the fact of 657000 events per year [1], [3] in the entire world. As our environment size is 8% of the entire world, we may assume a proportional 52662 per year. Assuming an even distribution of this number of events in our environment 5266/(N_1xM_1)=8.22 H50: Assumption of 1600 events per year in the entire environment, or 1600/(N1xM1)=0.25 events per sector S1 per year.[2] H51: Based on the [3], 52 icing accidents in 5 years [1], or 10.4 per year. Assuming that 100 times more flights experienced icing condition but successfully avoided them, result in 1040 events/year, or 0.16 events per year per sector S1. Overall: H44: $8.22\frac{events}{year}$ $per\ S_1$, with a mean duration of 1800s each

			$\text{H50: } 0.25\frac{events}{year}\ per\ S_1, \text{with a mean duration of } 1800s \text{ each}$ $\text{H51: } 0.16\frac{events}{year}\ per\ S_1, \text{with a mean duration of } 1800s \text{ each}$ $8.63\frac{events}{year}\ per\ S_1, \text{ in total} \rightarrow p_{non}^{EN\_GH1} = 0.0005$ $\Delta t_{EN\_HZ\_D2} = \mu_{EN}^{HG1}\frac{1-p_{non}^{EN\_GH1}}{p_{non}^{EN\_GH1}} = 3600000s$ $\Delta t_{EN\_HZ\_D1} = \mu_{EN}^{HG1} = 1800s$
μ_{EN}^{HG1}	Mean duration of the hazards group 1 triggering	$1800s$	Source: [4]

[1] https://www.nssl.noaa.gov/education/svrwx101/thunderstorms/

[2] https://www.weather.gov/source/zhu/ZHU_Training_Page/turbulence_stuff/turbulence/turbulence.htm

[3]https://ral.ucar.edu/sites/default/files/public/events/2015/in-flight-icing-users-technical-interchange-meeting-tim/docs/eick-ntsb-ncar-icing-presentation.pdf

[4]https://www.weather.gov/bgm/severedefinitions

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

There are outgoing arcs to Environment EN

- EN uses the information from EN_HZ to render airspace sectors S_1 , available or unavailable

Incoming arcs from other agents

None.

Outgoing arcs to other agents

None.

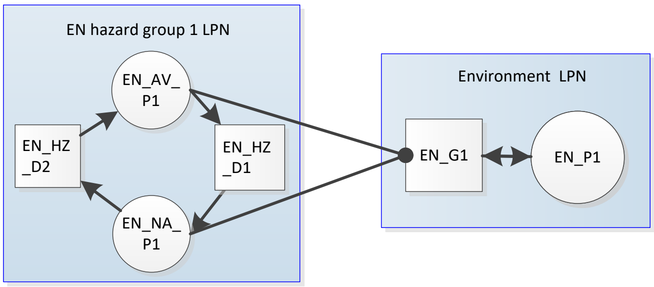

Figure 27 Hazards group 1 LPN interactions

Environment’s hazards group 2 LPN

- EN_AV_P2: All sectors S2 are available.
- EN_NA_P2: There is one sector S2 that is not available due to Airspace closures re-entry of a satellite (controlled/uncontrolled, space debris or Space weather

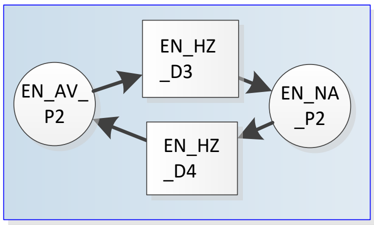

Figure 28 Environment's hazards LPN Hazards group 2

Colour type

Colour type	**Notation**	**State Space**	**Description**
EN_HZ_2	$S_2^{n_2,m_2,t}$	$\{true,\ false\}$	Matrix of size $N_2 \cdot M_2$. Each sector $S_2^{n_2,m_2,t}$ may be available (true) or not available (false) due to the hazards of the group.

Colour function

Place	**Colour type**	**Colour function**
EN_AV_P2	EN_HZ_2	constant
EN_NA_P2	EN_HZ_2	constant

Initial marking

Place	Initial Colour
EN_AV_P2	A token with colour EN_HZ_2: $\forall n_2 \in N_2, \forall m_2 \in M_2, \forall t \in T:\ S_2^{n_2,m_2,t} = true$

Delay transitions

Transition	Delay rate	Firing function
EN_ HZ_D3: EN_AV_P2→ EN_NA_P2	Delay ~ Exp($\Delta t_{EN\_HZ\_D3}$)	A token with colour EN_HZ_2: $\forall n_2 \in N_2, \forall m_2 \in M_2, \forall t \in [t,\ldots,T]$ $S_2^{n_2,m_2,t} = true$
EN_HZ_D4: EN_NA_P2→EN_AV_P2	Delay ~ Exp($\Delta t_{EN\_HZ\_D4}$)	A token with colour EN_HZ_2: $for \text{ one pair } n_2, m_2 \in [N_2, M_2]$ $S_2^{n_2,m_2,t} = false$

Parameters

Parameters	**Description**	**Value**	**Explanation**
$p_{non}^{EN\_GH2}$	The probability that a token will be at the place EN_NA_P1	0.00005	H62: Assumption of 1 event per year in the entire world. As our environment size is 8% of the entire world, we may assume a proportional 0.08 events per year. H66: Assumption of 1 event per year with the same scaling assumption.

			We also assume that both events take place for a mean time of $10800s$ H62: $0.08\frac{events}{year}$, with a mean duration of $18000s$ each H66: $0.08\frac{events}{year}$, with a mean duration of $10800s$ each $0.16\frac{events}{year}$ in total $\rightarrow p_{non}^{EN\_GH2} = 0.00005$ $\Delta t_{EN\_HZ\_D4} = \mu_{EN}^{HG2}\frac{1-p_{non}^{EN\_GH2}}{p_{non}^{EN\_GH2}} = 215989200s$ $\Delta t_{EN\_HZ\_D3} = \mu_{EN}^{HG2} = 10800s$
μ_{EN}^{HG2}	Mean duration of the hazards group 2 triggering	$10800s$	Chosen as a reasonable time for the duration of these hazards

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

There are outgoing arcs to Environment EN:

- EN uses the information from EN_HZ to render airspace sectors S_2, available or unavailable.

Incoming arcs from other agents

None.

Outgoing arcs to other agents

None

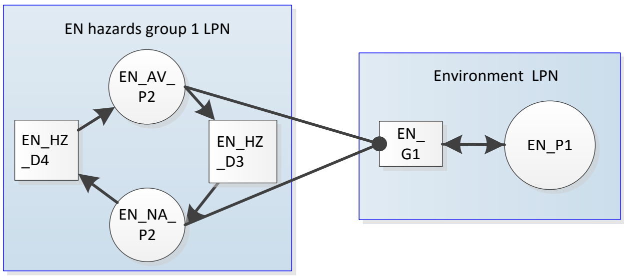

Figure 29 Hazards group 2 LPN interactions

Environment's hazards group 3 LPN

- EN_AV_P3: All sectors S3 are available.
- EN_NA_P3: There is one sector S3 that is not available due to Armed Conflict-military manned and unmanned operations, Volcanic Eruption, Hurricane

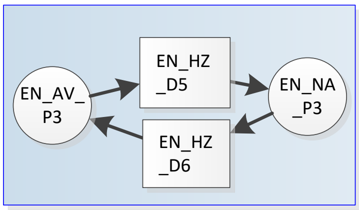

Figure 30 Environment's hazards LPN Hazards group 3

Colour type

Colour type	**Notation**	**State Space**	**Description**
EN_HZ_3	$S_3^{n_3,m_3,t}$	$\{true,\ false\}$	Matrix of size $N_3 x M_3$. Each sector $S_3^{n_3,m_3,t}$ may be available (true) or not available (false) due to the group hazards

Colour function

Place	**Colour type**	**Colour function**
EN_AV_P3	EN_HZ_3	constant
EN_NA_P3	EN_HZ_3	constant

Initial marking

Place	Initial Colour
EN_AV_P3	A token with colour EN_HZ_3 $\forall n_3 \in N_3, \forall m_3 \in M_3, \forall t \in T : S_3^{n_3,m_3,t} = true$

Delay transitions

Transition	Delay rate	Firing function
EN_ HZ_D5: EN_AV_P3→ EN_NA_P3	Delay~ Exp(Δt$_{EN\_HZ\_D5}$)	A token with colour EN_HZ_3 $\forall n_3 \in N_3, \forall m_3 \in M_3$: $S_3^{n_3,m_3,t} = true$
EN_ HZ_D6: EN_NA_P3→ EN_AV_P3	Delay~ Exp(Δt$_{EN\_HZ\_D6}$)	A token with colour EN_HZ_3 For one random pair of $n_3, m_3 \in [N_3, M_3]$ $S_3^{n_3,m_3,t} = false$

Parameters

Parameters	**Description**	**Value**	**Explanation**
$p_{non}^{EN\_GH3}$	The probability that a token will be at the place EN_NA_P5	$86400s$	H63: Assumption of 1 event per 10 years in the entire world. As our environment size is 8% of the entire world, we may assume a proportional 0.008 events per year. H64: Assumption of 1 event per year in the entire world. Same as before, we assume 0.08 events per year. H65: Assumption of 1 event per year in the entire

			world. Again, we assume 0.08 events per year. $for\ 1.2\frac{events}{year}, p_{non}^{EN\_GH3} = 0.0007$ $\Delta t_{\mathrm{EN\_HZ\_D6}} = \mu_{EN}^{HG3}\frac{1-p_{non}^{EN\_GH3}}{p_{non}^{EN\_GH3}} = 25696285s$ $\Delta t_{\mathrm{EN\_HZ\_D5}} = \mu_{EN}^{HG3} = 18000s$
μ_{EN}^{HG3}	Mean duration of the hazards group 3 triggering	$18000s$	Despite the fact that such hazards, upon triggering, take place for several days, we only consider a 18000s time. This is because we assume that only flights already airborne should be affected by these hazards, and we consider that flights more than 5 hours away from the sector have enough time to react appropriately.

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

There are outgoing arcs to Environment EN:

- EN uses the information from EN_HZ to render airspace sectors S_3, available or unavailable.

Incoming arcs from other agents

None.

Outgoing arcs to other agents

None.

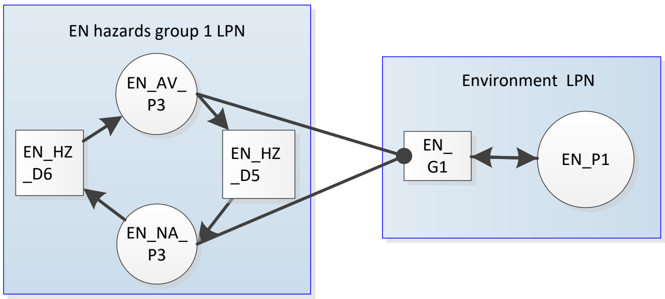

Figure 31 Hazards group 3 LPN interactions

D.4 Airport (AP)

Assumptions

1. All airports can be used by all aircraft types.
2. All airports are located at the same altitude, namely at the standard mean sea level (0m).
3. Each airport is a separate agent.

4. Airport weather hazards considered are of various types, with different delay impacts. In our model, we have grouped the most menacing weather hazards in five groups, with respect to the time delay they usually occur, as shown in
5.
6. Table 61.

Table 61 Airport weather hazards groups.

Weather type	**Range and mean delay occurred in minutes**
1	5-15 (10)
2	15-25 (20)
3	25-35 (30)
4	35-45 (40)
5	45-55 (50)

7. The identified hazards related to airport operations delays were grouped into six groups. Four of them concern the approach phase and two the departure phase of the flight. In Table 62 these groups are presented.

Table 62 Airport operational delays groups

Hazards group name	Event description	Corresponding Delay transition	Hazards' serial numbers
AP_HZ_G1	ATFM delays during the approach	AP_HZG_D1	H85, H86, H97, H99
AP_HZ_G2	Runway Unavailable(approach)	AP_ HZG _D2	H93, H96, H98
AP_HZ_G3	Unsafe finals (approach)	AP_ HZG _D3	H67, H68, H79
AP_HZ_G4	Airport unavailable(approach)	AP_ HZG _D4	H88, H89
AP_HZ_G5	Delays during taxing(departure)	AP_ HZG _D5	H96, H98
AP_HZ_G6	Delays at the gate (departure)	AP_ HZG _D6	H82, H86, H90

8. Flight crew and dispatch office can acquire the airport weather data through the Meteorological Office agent.
9. According to Eurocontrol Performance Review Report (PRR) 2019, in 2018, 2% of all flights were delayed due to weather at airports. From those flights, an average of 23 minutes of delay per flight was counted. Assuming that the delays data are representative for the entire world operations and also follow a (truncated for the positive values) normal distribution, we find the delay times at airports due to weather for the five types of weather incurred delays. Setting the parameters of the normal distribution as: mean

$\mu = 23\text{min}$ (according to Eurocontrol 2019 PRR) and $\sigma = 12\text{min}$ (assumption based on the grouping), we distribute the flights' delay times into five different (weather incurred) delays (grouped with respect to duration), as shown in Table 63. In more detail, as only 2% were delayed due to weather, the first row of Table 63 corresponds to 98% of the flights (no delays). Towards distributing the total number of flights into weather delays, we mentioned we assumed a truncated normal distribution. As such, we obtain the third column of the table, in which we summarize the probability of a flight to be delayed by the corresponding duration (of column 2). But, as only 2% of the flights were delayed due to weather, we multiply the estimated probability with 2%, providing the probability of a random flight being delayed by any weather type.

Table 63 Weather type and delays incurred

Delays incurring weather type	Mean duration of the delay (in min)	Probability of delays with a duration between the values of the range	Probability of delay by the corresponding duration, provided that the flight is delayed due to weather
0	0 (no delay)	0	0.98
1	10	0.25	0.005
2	20	0.32	0.0064
3	30	0.20	0.004
4	40	0.07	0.0014
5	50	0.01	0.0002

10. Airports (60 in total) are clustered into 5 groups, as shown in Table 64. Group 1 includes departure airports. Group 2 includes arrival airports for scenario 1, which refers to normal continental operations. Group 3 includes en-route alternate airports for scenario 2, so it should be considered only for scenario 2; finally, groups 4 and 5 include the arrival airports for scenario 2, 3a and 3b respectively.

Airport characteristics (AP_CH) LPN

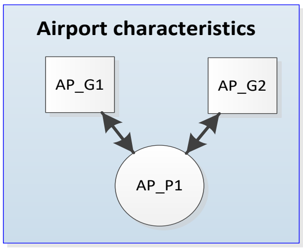

Figure 32 Airport LPN

Colour type

Colour type	**Notation**	**State Space**	**Description**
AP	$x^i_{1,AP}, y^i_{1,AP}$	$\mathbb{Z}^2$	airport i location
	t_{taxi}	$\mathbb{R}$	Taxi time
	C^{tx}_i	$\{true, false\}$	Taxi procedure completion condition at the airport i

Colour function

Place	**Colour type**	**Colour function**
AP_P1	AP	$dt^{I^{DEP}}_{tx,AP} = -dt$ $dt^{I^{ARR}}_{tx,AP} = -dt$

Initial marking

Place	Initial Colour
AP_P1	A token with colour AP: $\forall i \in I:$ $x^i_A = m^i_{1,AP} d^{S_1}_{sec}$ $y^i_A = n^i_{1,AP} d^{S_1}_{sec}$ $C^{tx}_i = false$

Guard transitions

Transition	Guard condition	Firing function
AP_G1: AP_P1→AP_P1	$t^{I^{DEP}}_{tx,AP} <= 0 \wedge F^S_{AC\_EV} = 1$	$C^{tx}_{I_{DEP}} = true$
AP_G2: AP_P1→AP_P1	$t^{I^{ARR}}_{tx,AP} <= 0 \wedge F^S_{AC\_EV} = 8$	$C^{tx}_{I^{ARR}} = true$

Parameters

Parameters	**Description**	**Value**	**Explanation**
$t^i_{tx}, \sigma^i_{tx}, t^i_{tx,min}, t^i_{tx,max}$	Truncated normal distribution parameters of taxiing time at the airport i	According to Table 64	Typical taxi times for airports [1]
$m^i_{1,AP}$ $n^i_{1,AP}$	S_1 sector at which the airport is located	According to Table 64	The position of the airport was selected, to facilitate the scenarios
N_{AP}	Number of airports	60	Table 64
I	Set of airports	$[1, 2, 3, 4, \ldots, N_{AP}]$	Table 64Table 64 Airport characteristics
h_{MA}	Altitude at which the missed approach is executed	$350m$	ILS CAT2 minima [2]

[1] Estimation of Aircraft Taxi-out Fuel Burn using Flight Data Recorder Archives, Harshad Khadilkar and Hamsa Balakrishnany, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[2] https://www.skybrary.aero/index.php/Work_in_progress:Precision_Approach

Table 64 Airport characteristics

Group index (used in the scenario)	**Airport index** i	$n^i_{1,AP}$	$m^i_{1,AP}$	$(t^i_{tx}, \sigma^i_{tx}, t^i_{tx,min}, t^i_{tx,max})$ (in min)	**Group index (used in the scenario)**	**Airport index** i	$n^i_{1,AP}$	$m^i_{1,AP}$	$(t^i_{tx}, \sigma^i_{tx}, t^i_{tx,min}, t^i_{tx,max})$ (in min)
1 (1,2,3)	1	2	5	6,2,3,10		31	65	10	6,2,3,10
	2	3	7	5,2,3,11		32	67	11	4,3,3,14
	3	4	9	3,2,3,12		33	70	7	4,3,3,14
	4	7	11	4,3,3,10		34	72	12	4,3,3,14
	5	11	13	5,2,3,14		35	74	10	6,2,3,10
2 (1)	6	15	15	6,2,3,10		36	76	11	4,3,3,14
	7	17	17	5,4,3,14		37	78	7	4,3,3,14
	8	19	19	4,3,3,14		38	80	12	4,3,3,14
	9	21	21	7,2,4,12		39	82	10	6,2,3,12
	10	23	12	4,2,3,14		40	84	11	4,1,2,11
	11	25	28	5,3,3,14		41	85	13	6,2,3,10
	12	27	25	6,1,3,10		42	90	11	5,3,1,14
	13	29	19	4,3,3,14	4 (2,3a)	43	95	10	7,2,4,12
	14	31	3	5,2,3,14		44	100	19	5,2,3,14
	15	33	8	6,2,3,10		45	105	27	6,2,3,10
	16	35	9	5,3,3,11		46	110	15	5,3,3,14
	17	37	10	2,1,3,10		47	115	7	6,2,3,10
	18	39	11	3,3,3,13		48	120	19	7,2,4,12
	19	41	7	4,3,3,14		49	125	17	5,3,3,14
	20	43	18	4,1,3,12		50	130	25	4,3,3,14
	21	45	12	5,2,3,14	5 (2.3b)	51	135	14	7,2,4,12
	22	47	8	6,1,3,10		52	140	15	4,3,3,14
	23	49	19	5,3,3,14		53	145	19	6,2,3,10
	24	51	28	6,2,3,10		54	150	25	7,2,4,12
	25	53	19	4,3,3,12		55	155	24	4,3,3,14
	26	55	15	3,3,2,11		56	160	25	5,3,3,14
	27	57	24	4,3,3,10		57	165	26	5,3,3,14
	28	59	12	5,2,3,14		58	167	25	5,3,3,14
3 (2)	29	61	8	6,2,3,10		59	168	28	5,3,3,14
	30	63	9	5,3,3,14		60	170	27	6,2,3,10

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

None.

Incoming arcs from other agents

None.

Outgoing arcs to other agents

There are outgoing arcs from AP to FC, AD, ATCo, FMS

- Flight Crew PL receives information about airport characteristics and taxi time.
- Airline Dispatch creates the flight plan upon receiving the same airport characteristics as the Flight Crew planning.
- ATCo_SA receives information about airport hazards.
- FMS receives the positions of all airports.

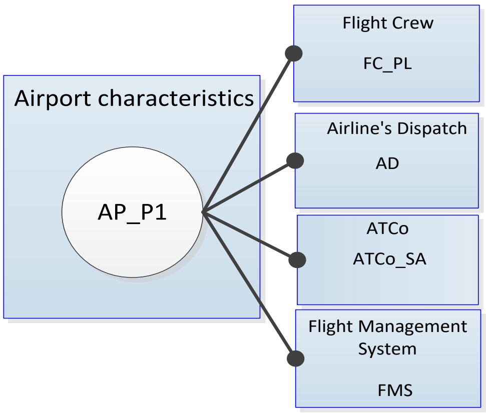

Figure 33 Airport LPN interactions

Airport Weather AP_WX LPN

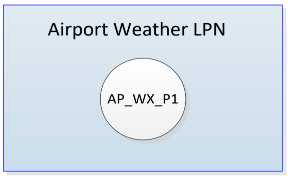

Figure 34 Airport weather LPN

Colour type

Colour type	Notation	State Space	Description
AP_WX	$W_{AP}^{i,t}$	$[0,1,2,3,4,5]$	Matrix of weather phenomena taking place at the airport i, at time t. Only one weather group (1-5) may occur at any time point for a specific airport. Zero value means no phenomena are taking place.

Colour function

Place	**Colour type**	**Colour function**
AP_WX_P1	A token with colour AP_WX	constant

Initial marking

Place	Initial Colour
AP_ WX_P1	A token with colour AP_WX: $\forall i \in I:$ $W_{AP}^{i,t} = \left\{ \begin{array}{l} 0, \text{with probability } \mathrm{P}_{\mathrm{wx0}} \\ 1, \text{with probability } \mathrm{P}_{\mathrm{wx1}}, \text{for } \mathrm{N}(\mathrm{t}_{wx}^{1}, \sigma_{wx}) \text{ consecutive t} \\ 2, \text{with probability } \mathrm{P}_{\mathrm{wx2}}, \text{for } \mathrm{N}(\mathrm{t}_{wx}^{2}, \sigma_{wx}) \text{ consecutive t} \\ 3, \text{with probability } \mathrm{P}_{\mathrm{wx3}}, \text{for } \mathrm{N}(\mathrm{t}_{wx}^{3}, \sigma_{wx}) \text{ consecutive t} \\ 4, \text{with probability } \mathrm{P}_{\mathrm{wx4}}, \text{for } \mathrm{N}(\mathrm{t}_{wx}^{4}, \sigma_{wx}) \text{ consecutive t} \\ 5, \text{with probability } \mathrm{P}_{\mathrm{wx5}}, \text{for } \mathrm{N}(\mathrm{t}_{wx}^{5}, \sigma_{wx}) \text{ consecutive t} \end{array} \right\}$

Parameters

Parameters	**Description**	**Value**	**Explanation**
P_{wx0}	Probability of no weather phenomena happening at the airport i	0.98	Table 63
P_{wx1}	Probability of weather type 1 happening at the airport i	0.0057	Table 63
P_{wx2}	Probability of weather type 2 happening at the airport i	0.0075	Table 63
P_{wx3}	Probability of weather type 3 happening at the airport i	0.0052	Table 63
P_{wx4}	Probability of weather type 4 happening at the airport i	0.0014	Table 63
P_{wx5}	Probability of weather type 5 happening at the airport i	0.0002	Table 63
t_{wx}^{1}, σ_{wx}	Mean duration and standard deviation of weather type 1	$600s, 300s$	Table 63
t_{wx}^{2}, σ_{wx}	Mean duration and standard deviation of weather type 2	$1200s, 300s$	Table 63
t_{wx}^{3}, σ_{wx}	Mean duration and standard deviation of weather type 3	$1800s, 300s$	Table 63
t_{wx}^{4}, σ_{wx}	Mean duration and standard deviation of weather type 4	$2400s, 300s$	Table 63
t_{wx}^{5}, σ_{wx}	Mean duration and standard deviation of weather type 5	$3000s, 300s$	Table 63

Incoming arcs within the same agent.

None.

Outgoing arcs within the same agent

There is one arc to MET LPN.

- MET agent received the weather matrix of the airports and produce the weather forecast

Incoming arcs from other agents

None.

Outgoing arcs to other agents

None.

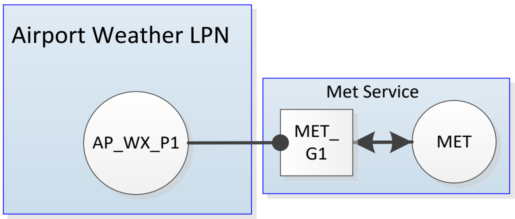

Figure 35 Airport weather LPN and interactions

Airport Hazards group 1 LPN (AP_HZ_G1)

- Each airport is modelled by one identical but separate LPN.
- AP_P_HG1: Nominal condition, no operational delays due to hazards group 1.
- AP_P_HG1T: Non-nominal condition, operational delays due to hazards group 1 are expected.

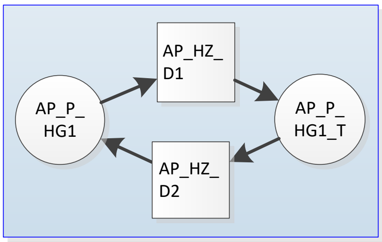

Figure 36 Airport hazards group 1 LPN

Colour type

Colour type	**Notation**	**State Space**	**Description**
AP_HZ_G1	$t_i^{AP,1}$	$\mathbb{R}^+$	Delays during approach for the airport i . If delays occur during the approach, the aircraft will proceed to hold procedure. The value of this variable indicates the mean duration of delays, while a zero value means that there is no delay. This value is used by ATCo and FC to determine the duration of the delays.

Colour function

Place	**Colour type**	**Colour function**
AP_P_HG1	A token with colour AP_HZ_G1	constant
AP_P_HG1_T	No token	constant

Delay transitions

Transition	Delay rate	Firing function
AP_HZ_D1: AP_P_HG1 → AP_P_HG1_T	Delay ~ Exp($\Delta t_{AP\_HZ\_D1}$)	A token with colour AP_HZ_G1 $t_i^{AP,1} = f_E(\mu_{AP,i}^{app,1})$
AP_HZ_D2: AP_P_HG1_T → AP_P_HG1	Delay ~ Exp($\Delta t_{AP\_HZ\_D2}$)	A token with colour AP_HZ_G1 $t_i^{AP,1} = 0$

Parameters

Parameters	**Description**	**Value**	**Explanation**
$p_{non}^{AP\_HG\_1}$	Probability of occurrence	0.3	According to [1], the average delay per arrival is 13min, 37.4 % were capacity-ATFM airport-related, thus 37.4% of flights were delayed for μ=13min]. As we are only interested in unexpected delays, we arbitrarily assume that 1% of those incurred while the flight was already in flight, and thus the pilots did not count for them. Consequently a final probability of 0.37% of capacity-ATFM delays for every airport. *All values are per airport $p_{non}^{AP\_HG\_1} = 0.0037$ $\Delta t_{AP\_HZ\_G1} = \mu_{non}^{AP1} \frac{1-p_{non}^{AP\_HG\_1}}{p_{non}^{AP\_HG\_1}} = 193874s$ $\Delta t_{AP\_HZ\_G2} = \mu_{non}^{AP1} = 720s$
$\mu_{AP,i}^{app,1}$	Mean delay time due to AP_HG_1	193874 s	As calculated above

[1]Eurocontrol Performance Review Report (PRR)], in 2018

Incoming arcs within the same agent.

None.

Outgoing arcs within the same agent

None.

Incoming arcs from other agents

None.

Outgoing arcs to other agents

There is an outgoing arc to ATCo_SA

- ATCo_SA receives information about the delays at the airports.

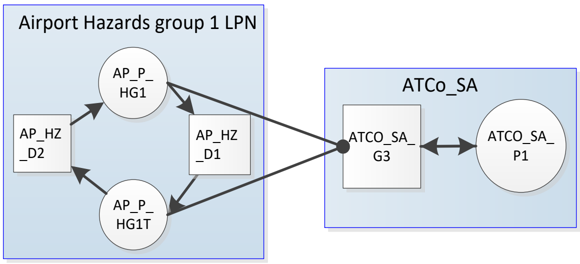

Figure 37 Airport Hazards group 1 LPN (delays during approach)

Airport Hazards group 2 LPN (AP_HZ_G2)

- Each airport is modelled by one identical but separate LPN.
- AP_P_HG2: Nominal condition, no operational delays due to hazards group 2.
- AP_P_HG2T: Non-nominal condition, operational delays due to hazards group 2 are expected.

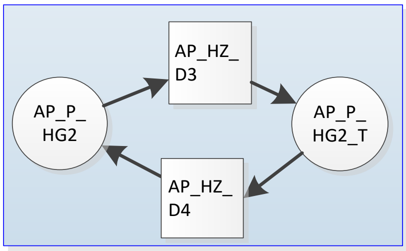

Figure 38 Airport hazards group 2

Colour type

Colour type	Notation	State Space	Description
AP_HZ_G2	$t_i^{AP,2}$	$\mathbb{R}^+$	Runway availability of airport i . If the runway is not available during the approach, the aircraft will proceed to a missed approach procedure. The value of this variable indicates the duration of unavailability, while a zero value means that the runway is available. This value is used by ATCo and FC to determine the duration of the delays.

Colour function

Place	Colour type	Colour function
AP_P_HG2	A token with colour AP_HZ_G2	constant
AP_P_HG2_T	No token	constant

Delay transitions

Transition	Delay rate	Firing function
AP_HZ_D3: AP_P_HG2 → AP_P_HG2_T	Delay ~ Exp($\Delta t_{AP\_HZ\_D3}$)	A token with colour AP_HZ_G2 $t_i^{AP,2} = f_E(\mu_{AP,i}^{app,2})$
AP_HZ_D4: AP_P_HG2_T →AP_P_HG2	Delay ~ Exp($\Delta t_{AP\_HZ\_D4}$)	A token with colour AP_HZ_G2 $t_i^{AP,2} = 0$

Parameters

Parameters	**Description**	**Value**	**Explanation**
$p_{non}^{AP\_HG\_2}$	Probability of occurrence	0.3	H98: Assumption of 1event/year H96: (hazard considered for non-scheduled events, during operations): Assumption of 5 events/year H93 Runway incursion ~45/year in 2018 for one major multiple-runway European Airport (Amsterdam Airport Schiphol) [1]. As from those events, only 8 were classified as of higher severity, while the rest as of lower, we assume that only those provoked go-around procedures for other traffic. Additionally, as the specific airport is considered as complex in taxing, we assume that 5 events per year would be a more representative number of incursions, for an average airport. Summing up, we have 11 events per year. We assume that all events have a mean duration of 15min. *All values are per airport $p_{non}^{AP\_HG\_2} = 0.0003$ $\Delta t_{AP\_HZ\_G3} = \mu_{non}^{AP2} \frac{1 - p_{non}^{AP\_HG\_2}}{p_{non}^{AP\_HG\_2}} = 2999100s$ $\Delta t_{AP\_HZ\_G4} = \mu_{non}^{AP2} = 900s$
$\mu_{AP,i}^{app,2}$	Mean delay caused by AP_HG_2	193874 s	As calculated above

[1] https://en.lvnl.nl/safety/categories-of-incidents/runway-incursion

Incoming arcs within the same agent.

None.

Outgoing arcs within the same agent

None.

Incoming arcs from other agents

None.

Outgoing arcs to other agents

There is an outgoing arc to ATCo_SA

- ATCo_SA receives information about the delays at the airports.

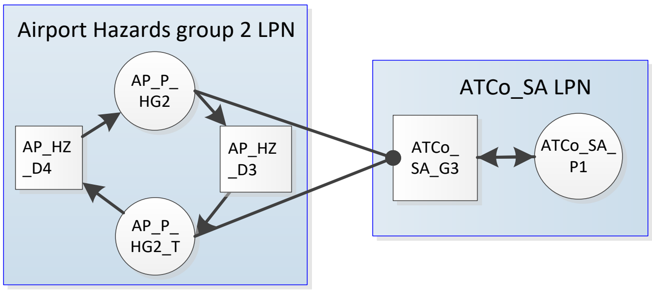

Figure 39 Airport Hazards group 2 LPN (runway unavailable)

Airport Hazards group 3 LPN (AP_HZ_G3)

- Each airport is modelled by one identical but separate LPN.
- AP_P_HG3: Nominal condition, no operational delays due to hazards group 3.
- AP_P_HG3T: Non-nominal conditions, operational delays due to hazards group 3 are expected.

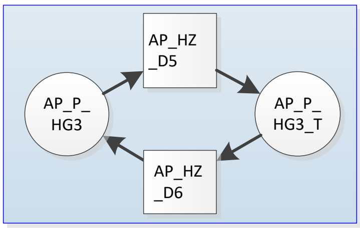

Figure 40 Airports hazards group 3

Colour type

Colour type	Notation	State Space	Description
AP_HZ_G3	$t_i^{AP,3}$	$\mathbb{R}^+$	Runway finals condition safety for the airport i . In the non-safe condition, the aircraft will proceed to a missed approach procedure. The value of this variable indicates the duration of triggering, while a zero value means that the runway is safe. This value is used by ATCo and FC to determine the duration of the delays.

Colour function

Place	Colour type	Colour function
AP_P_HG3	A token with colour AP_HZ_G3	constant
AP_P_HG3_T	No token	constant

Delay transitions

Transition	Delay rate	Firing function
AP_HZ_D5: AP_P_HG3 → AP_P_HG3_T	Delay ~ Exp($\Delta t_{AP\_HZ\_D5}$)	A token with colour AP_HZ_G3 $t_i^{AP,3} = f_E(\mu_{AP,i}^{app,3})$
AP_HZ_D6: AP_P_HG3_T → AP_P_HG3	Delay ~ Exp($\Delta t_{AP\_HZ\_D6}$)	A token with colour AP_HZ_G3 $t_i^{AP,3} = 0$

Parameters

Parameters	**Description**	**Value**	**Explanation**
$p_{non}^{AP\_HG\_3}$	Probability of occurrence	0.0006	H67,68,69: Assumption of 5 events/year *All values are per airport $p_{non}^{AP\_HG\_3} = 0.0006$ $\Delta t_{AP\_HZ\_G5} = \mu_{non}^{AP3} \frac{1 - p_{non}^{AP\_HG\_3}}{p_{non}^{AP\_HG\_3}} = 5996400s$ $\Delta t_{AP\_HZ\_G6} = \mu_{non}^{AP3} = 3600s$
$\mu_{AP,i}^{app,3}$	Mean delay caused by AP_HG_3	$3600s$	We assume a mean duration of the phenomenon to be $\mu_{non}^{AP3} = 3600s$

Incoming arcs within the same agent.

None.

Outgoing arcs within the same agent

None.

Incoming arcs from other agents

None.

Outgoing arcs to other agents

None.

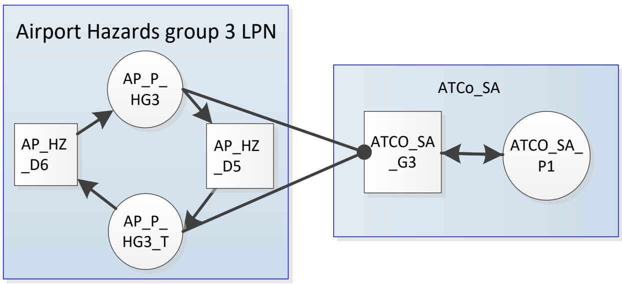

Figure 41 Airport Hazards group 3 LPN (unsafe finals)

Airport Hazards group 4 LPN (AP_HZ_G4)

- Each airport is modelled by one identical but separate LPN.
- AP_P_HG4: Nominal condition, no operational delays due to hazards group 4.

- AP_P_HG4T: Non-nominal conditions, operational delays due to hazards group 4 are expected.

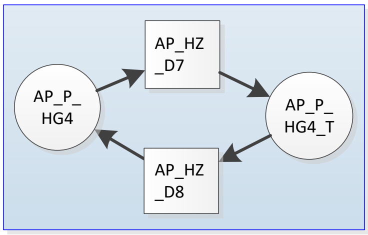

Figure 42 Airport Hazards group 4 LPN

Colour type

Colour type	**Notation**	**State Space**	**Description**
AP_HZ_G4	$t_i^{AP,4}$	$\mathbb{R}^+$	Availability of the airport i. When the airport is not available, the aircraft will proceed to hold procedure or divert. The value of this variable indicates the duration of unavailability, while a zero value means that the airport is available. This value is used by ATCo and FC to determine the delays' duration.

Colour function

Place	**Colour type**	**Colour function**
AP_P_HG4	A token with colour AP_HZ_G4	constant
AP_P_HG4_T	No token	constant

Delay transitions

Transition	Delay rate	Firing function
AP_HZ_D7: AP_P_HG4→AP_P_HG4_T	Delay ~ Exp($\Delta t_{AP\_HZ\_D7}$)	A token with colour AP_HZ_G4 $t_i^{AP,4} = f_E(\mu_{AP,i}^{app,4})$
AP_HZ_D8: AP_P_HG4_T→ AP_P_HG4	Delay ~ Exp($\Delta t_{AP\_HZ\_D8}$)	A token with colour AP_HZ_G4 $t_i^{AP,4} = 0$

Parameters

Parameters	**Description**	**Value**	**Explanation**
$p_{non}^{AP\_HG\_4}$	Probability of occurrence	0.00006	H88,89: Assumption of 0.1 events/year *All values are per airport $p_{non}^{AP\_HG\_4} = 0.00006$ $\Delta t_{AP\_HZ\_G7} = \mu_{non}^{AP4} \frac{1 - p_{non}^{AP\_HG\_4}}{p_{non}^{AP\_HG\_4}} = 299982877s$ $\Delta t_{AP\_HZ\_G8} = \mu_{non}^{AP4} = 18000s$
$\mu_{AP,i}^{app,4}$	Mean delay caused by	$18000s$	We assume a mean duration of the phenomenon to be $\mu_{non}^{AP4} = 18000s$ Despite such events may last longer [1], we

	AP_HG_4		assume that after 5h all airborne flights will have enough time for addressing the airport unavailability safely. Non-airborne flights are not affected.

[1] https://en.wikipedia.org/wiki/Gatwick_Airport_drone_incident

Incoming arcs within the same agent.

None.

Outgoing arcs within the same agent

There is one arc to Airport LPN.

Incoming arcs from other agents

None.

Outgoing arcs to other agents

None.

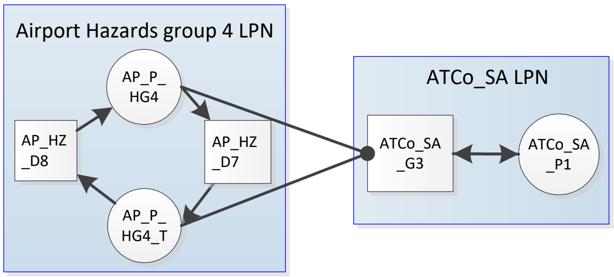

Figure 43 Airport Hazards group 4 LPN (airport unavailable)

Airport Hazards group 5 LPN (AP_HZ_G5)

- Each airport is modelled by one identical but separate LPN.
- AP_P_HG5: Nominal condition, no operational delays due to hazards group 5.
- AP_P_HG5T: Non-nominal conditions, operational delays due to hazards group 5 are expected.

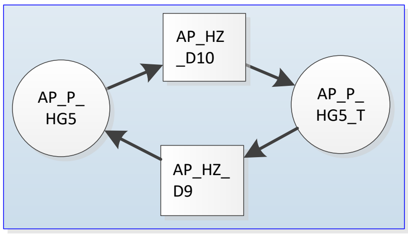

Figure 44 Airport Hazards group 5 LPN

Colour type

Colour type	**Notation**	**State Space**	**Description**
AP_HZ_G5	$t_i^{AP,5}$	$\mathbb{R}^+$	Duration of delays during departure/taxi out for the airport i . If ground delays occur, the aircraft’s take-off will be delayed. A zero value means that there is no delay.

Colour function

Place	Colour type	Colour function
AP_P_HG5	A token with colour AP_HZ_G5	constant
AP_P_HG5_T	No token	constant

Delay transitions

Transition	Delay rate	Firing function
AP_HZ_D9: AP_P_HG5_T→AP_P_HG5	Delay ~ Exp($\Delta t_{AP\_HZ\_D9}$)	A token with colour AP_HZ_G5 $t_i^{AP,5} = 0$
AP_HZ_D10: AP_P_HG5→ AP_P_HG5_T	Delay ~ Exp($\Delta t_{AP\_HZ\_D10}$)	A token with colour AP_HZ_G5 $\mu_{non}^{AP5} = f_E(\mu_{non}^{AP5})$

Parameters

Parameters	Description	Value	Explanation
$p_{non}^{AP\_HG\_5}$	Probability of occurrence	0.00034	H96: Assumption of 6 events/year H98: Assumption of 6 events/year *All values are per airport $p_{non}^{AP\_HG\_5} = 0.00034$ $\Delta t_{AP\_HZ\_G9} = \mu_{non}^{AP5} \frac{1-p_{non}^{AP\_HG\_5}}{p_{non}^{AP\_HG\_5}} = 2646158s$ $\Delta t_{AP\_HZ\_G10} = \mu_{non}^{AP5} = 900s$
μ_{non}^{AP5}	Mean delay caused by AP_HG_5	$900s$	We assume a mean duration of the phenomenon to be μ_{non}^{AP5} .

Incoming arcs within the same agent.

None.

Outgoing arcs within the same agent

There is one arc to Airport LPN.

Incoming arcs from other agents

None.

Outgoing arcs to other agents

None.

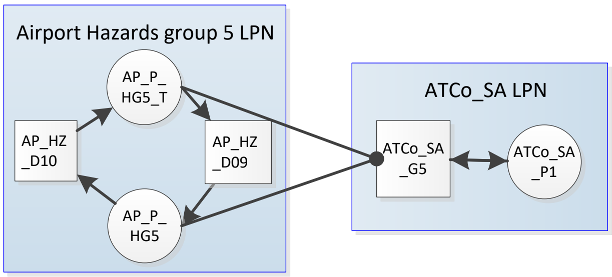

Figure 45 Airport Hazards group 5 LPN (delays during taxing-out/departure)

Airport Hazards group 6 LPN (AP_HZ_G6)

- Each airport is modelled by one identical but separate LPN.
- AP_P_HG6: Nominal condition, no operational delays due to hazards group 6.
- AP_P_HG6T: Non-nominal conditions, operational delays due to hazards group 6 are expected.

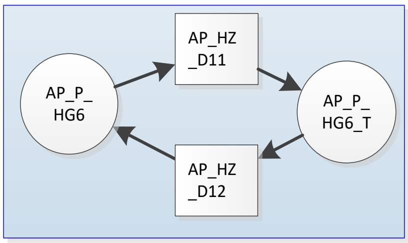

Figure 46 Airport hazards group 6 LPN

Colour type

Colour type	Notation	State Space	Description
AP_HZ_G6	$t_i^{AP,6}$	$\mathbb{R}^+$	Delays at the gate for the airport i . When the delays occur, the aircraft's start-up will be delayed. A zero value means that there is no delay.

Colour function

Place	Colour type	Colour function
AP_P_HG6	A token with colour AP_HZ_G6	constant
AP_P_HG6_T	No token	constant

Delay transitions

Transition	Delay rate	Firing function
AP_HZ_D11: AP_P_HG6 → AP_P_HG6_T	$\text{Delay} \sim \text{Exp}(\Delta t_{AP\_HZ\_D11})$	A token with colour AP_HZ_G6 $t_i^{AP,6} = f_E(\mu_{non}^{AP6})$
AP_HZ_D12: AP_P_HG6_T → AP_P_HG6	$\text{Delay} \sim \text{Exp}(\Delta t_{AP\_HZ\_D12})$	A token with colour AP_HZ_G6 $t_i^{AP,6} = 0$

Parameters

Parameters	Description	Value	Explanation
$p_{non}^{AP\_HG\_6}$	Probability of occurrence	0.005	H82: Assumption of 40 events/year H86: Assumption of 2 events/year H90: Assumption of 100 events/year *All values are per airport

			$p_{non}^{AP\_HG\_6} = 0.005$ $\Delta t_{AP\_HZ\_G11} = \mu_{non}^{AP6}\frac{1-p_{non}^{AP\_HG\_6}}{p_{non}^{AP\_HG\_6}} = 358054s$ $\Delta t_{AP\_HZ\_G12} = \mu_{non}^{AP6} = 1800s$
μ_{non}^{AP6}	Mean delay caused by AP_HG_6	$1800s$	We assume for these events to have a mean duration of μ_{non}^{AP6}.

Incoming arcs within the same agent.

None.

Outgoing arcs within the same agent

There is one arc to Airport LPN.

Incoming arcs from other agents

None.

Outgoing arcs to other agents

None.

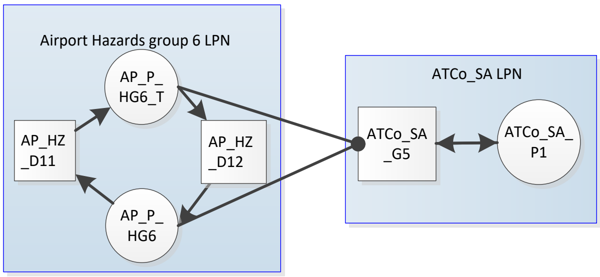

Figure 47 Airport Hazards group 6 LPN (delays at the gate)

D.5 Aircraft (AC)

Assumptions

1. The model considers six different types of aircraft, as illustrated in Table 65.
2. As of fuel leakage hazard, the maximum amount of fuel leakage is set to four times the Final Reserve Fuel (approximately two hours of flight).
3. The hazards modelled in AC_HZ are those of Table 66.

Table 65 Aircraft types considered

Mid-range (<5000km)	Long-range (5.000-12.000km)	Ultra-long range (>12.000km)
Boeing 737-800	Airbus 330-300	Boeing 787-9
Airbus A320-200		Airbus A350-900

Table 66 Simulated systems malfunctions

Notation	State Space	Description
ACHZ_1	{true, false}	Degraded Engines. Included in HZ_G1.
ACHZ_2	{true, false}	Landing gear malfunction. Included in HZ_G2
ACHZ_3	{true, false}	Damaged/dirty structure. Included in HZ_G3
ACHZ_4	{true, false}	Ice formation on the structure. Included in HZ_G4

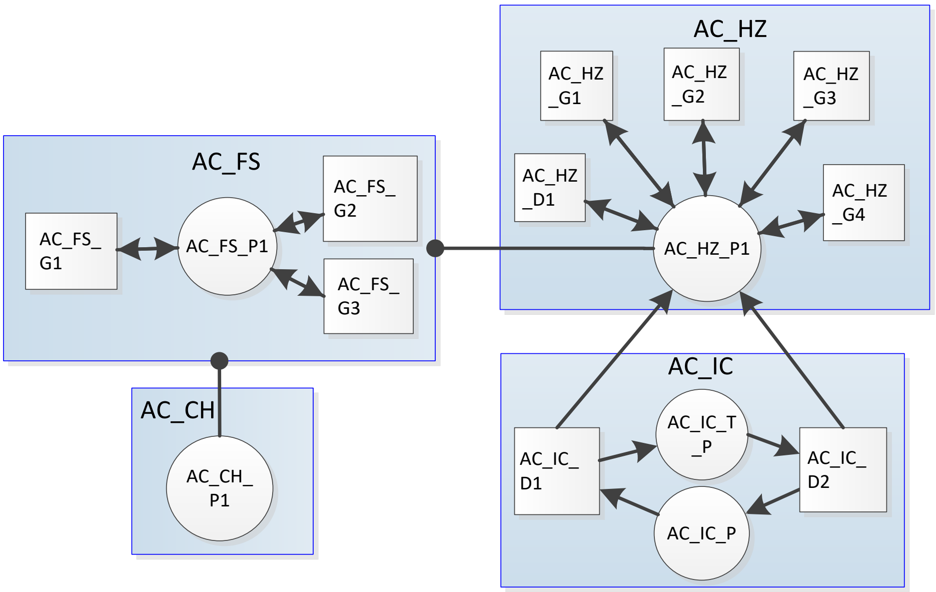

Figure 48 Aircraft LPNs interactions

Aircraft Characteristics LPN (AC_CH)

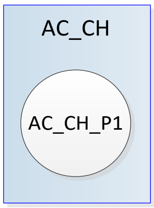

Figure 49 Aircraft characteristics LPN

Colour type

Colour type	Notation	State Space	Description
AC_CH	A_T	$[1,2,3,4,5]$	Aircraft type

Colour function

Place	Colour type	Colour function
AC_CH_P1	AC_CH	None

Initial marking

Place	Initial Colour
AC_CH_P1	A token with colour AC_CH

Parameters

Parameters	**Description**	**Value**	**Explanation**
A_C	Set of aircrafts	$[1,2,3,4,5]$	A representative set of contemporary and popular airlines aircraft was selected.

Aircraft Parameters

In the following table, the various aircraft parameters are demonstrated.

Table 67 Fuel consumption values and mass related parameters [39]

Parameters for all aircraft types (A_T)	Boeing 737-800	A320-231	A330-301	B787-9	A350-941
$m_0^{A_T}$	4.12E+04	3.90E+04	1.38E+05	1.47E+05	2.95E+05
$m_{\max}^{A_T}$	7.83E+04	7.70E+04	2.51E+05	2.75E+05	5.60E+05
$C_{tx}^{A_T}$	1.20E+01	1.40E+01	2.60E+01	2.60E+01	4.20E+01
$C_{APU}^{A_T}$	1.83E+00	2.1E+00	2.20E+00	5.20E+00	5.50E+00
$C_{f1}^{A_T}$	1.17E-05	1.26E-05	9.11E-06	8.15E-06	9.06E-06
$C_{f2}^{A_T}$	5.49E+02	1.51E+03	6.16E+02	4.89E+03	4.46E+03
$C_{f3}^{A_T}$	2.37E-01	1.49E-01	2.80E-01	3.28E-01	1.07E+00
$C_{f4}^{A_T}$	2.01E+04	2.86E+04	2.45E+04	3.93E+05	2.27E+04
$C_{fcr}^{A_T}$	9.30E-01	9.64E-01	9.14E-01	9.43E-01	9.31E-01
$C_{T1}^{A_T}$	1.47E+05	1.42E+05	3.70E+05	4.26E+05	8.87E+05
$C_{T2}^{A_T}$	1.64E+04	1.58E+04	1.86E+04	2.05E+04	1.71E+04
$C_{T3}^{A_T}$	3.28E-10	6.11E-10	7.44E-11	4.13E-10	1.42E-10
$C_{Tcr}^{A_T}$	9.50E-01	9.50E-01	9.50E-01	9.50E-01	9.50E-01
$C_{Tapp}^{A_T}$	1.94E-01	1.57E-01	8.91E-02	8.09E-02	1.92E-01
$C_{Tld}^{A_T}$	3.06E-01	3.96E-01	2.55E-01	9.09E-01	3.37E-01
$C_{D1}^{A_T}$	2.55E-02	2.67E-02	2.19E-02	2.10E-02	1.81E-02
$C_{D2}^{A_T}$	3.58E-02	3.87E-02	3.41E-02	4.05E-02	4.32E-02
S^{A_T}	1.25E+02	1.23E+02	3.60E+02	4.43E+02	8.45E+02
$h_{app}^{A_T}$	7.62E+02				
$h_{ld}^{A_T}$	10				

Table 68 Fuel consumption and mass related parameters. Source: [39]

Notation	Description	Unit
$m_0^{A_T}$	zero fuel weight	kg

$m_{\max}^{A_T}$	maximum weight	kg
$C_{tx}^{A_T}$	fuel flow during taxiing	$kg \cdot s^{-1}$
$C_{APU}^{A_T}$	fuel flow due to APU operation	$kg \cdot s^{-1}$
$C_{f1}^{A_T}$	thrust specific fuel consumption parameter	$kg \cdot s^{-1} \cdot N^{-1}$
$C_{f2}^{A_T}$	thrust specific fuel consumption parameter	$m \cdot s^{-1}$
$C_{f3}^{A_T}$	idle thrust fuel flow parameter	$kg \cdot s^{-1}$
$C_{f4}^{A_T}$	idle thrust fuel flow parameter	m
$C_{fcr}^{A_T}$	correction factor for fuel flow during the cruise	dimensionless
$C_{T1}^{A_T}$	thrust parameter	N
$C_{T2}^{A_T}$	thrust parameter	m
$C_{T3}^{A_T}$	thrust parameter	m^{-2}
$C_{Tcr}^{A_T}$	maximum cruise thrust correction factor	dimensionless
$C_{Tapp}^{A_T}$	approach thrust correction factor	dimensionless
$C_{Tld}^{A_T}$	landing thrust correction factor	dimensionless
$C_{D1}^{A_T}$	drag parameter	dimensionless
$C_{D2}^{A_T}$	drag parameter	dimensionless
S^{A_T}	wing reference area	m^2
$h_{app}^{A_T}$	altitude at which the formula for fuel flow during approach can be used	m
$h_{ld}^{A_T}$	altitude at which the formula for fuel flow during landing can be used	m

Other variables

Variable name	**Description**
$v_{cl,TAS}^{AT,h}$	A matrix containing the values of true airspeed during climb at altitude h for the aircraft type A_T
$v_{cr,TAS}^{AT,h}$	A matrix containing the values of true airspeed during cruise at altitude h for the aircraft type A_T
$v_{de,TAS}^{AT,h}$	A matrix containing the values of true airspeed during descent at altitude h for the aircraft type A_T
$v_{ROC}^{AT,h}$	A matrix containing the values of rate of climb at altitude h for the aircraft type A_T
$v_{ROD}^{AT,h}$	A matrix containing the values of rate of descent at altitude h for the aircraft type A_T
$d_{de,h}$	A matrix containing the values of distance the aircraft type A_T will travel before descending to ground from altitude h

Incoming arcs within the same agent.

None.

Outgoing arcs within the same agent

There is one arc to AC_FS.

Incoming arcs from other agents

None.

Outgoing arcs to other agents

- Airline Dispatch uses the parameters of the aircraft (fuel related) to calculate the fuel need for the flight.
- Aircraft Fuel Systems uses the fuel consumption parameters provided in AC_CH.

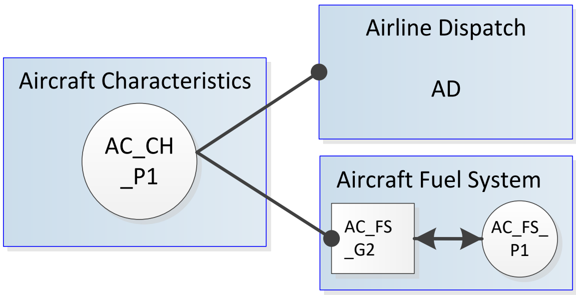

Figure 50 Aircraft Characteristics LPN interactions

Fuel System LPN (AC_FS)

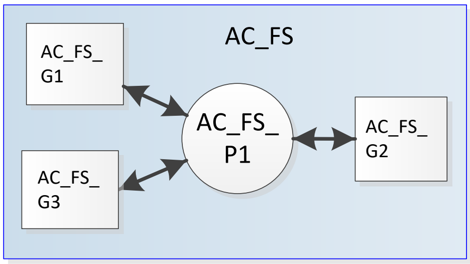

Figure 51 Aircraft Fuel System LPN

Colour type

Colour type	Notation	State Space	Description
AC_FS	f_f^{tot}	$\mathbb{R}_+$	Total fuel consumption
	$f_{ff,ENG}^{AT}$	$\mathbb{R}_+$	Nominal fuel flow due to aircraft’s engines operation for the specific phase of flight
	f_{ff,AC_FS}^{ENG}	$\mathbb{R}_+$	Actual fuel flow due to aircraft’s engines operation, including all factors that may increase the fuel flow
	f_{ff,AC_FS}^{APU}	$\mathbb{R}_+$	fuel flow due to APU operation
	f_{ff,AC_FS}^{ICE}	$\mathbb{R}_+$	Extra fuel flow due to wing/engine anti-ice operation
	m_f	$\mathbb{R}_+$	amount of fuel left in tanks
	f_{burnt}	$\mathbb{R}_+$	Fuel burnt at any time point
	$f_{leacked}$	$\mathbb{R}_+$	Fuel leaked at any time point

	$t_{timerFS}$	$\mathbb{R}_+$	timer for simulating the fuel flow
	$t_{timerFS2}$	$\mathbb{R}_+$	timer for update the fuel calculations

Colour function

Place	**Colour type**	**Colour function**
AC_FS_P1	AC_FS	$dm_f = -f_f^{tot} dt$ $df_{burnt} = f_f^{tot} dt$ $dt_{timerFS} = -dt$ $dt_{timerFS2} = -dt$

Initial marking

Place	Initial Colour
AC_FS_P1	A token with colour AC_FS

Guard transitions

Transition	Firing condition	Firing function
AC_FS_G1: AC_FS_P1 → AC_FS_P1	$F_{AC\_EV}^{S} = -1$	$m_f = m_{f,GH}^{actual,up}$ Variables used from other LPNs: • $m_{f,GH}^{actual,up}$ from GH
AC_FS_G2: AC_FS_P1 → AC_FS_P1	$t_{timerFS} \leq 0 \wedge F_{AC\_EV}^{S} \geq 0$	a token with colour FS: $t_{timerFS} = \Delta t_{timerFS}$ $if\ S_f^{FC\_AC} = ground$ $f_{ff,AC\_FS}^{APU} = C_{APU}^{A_T}$ $if\ S_f^{FC\_AC} = taxi$ $f_{ff,ENG}^{A_T} = C_{tx}^{A_T}$ $if\ S_f^{FC\_AC} = climb$ $f_{ff,ENG}^{A_T} = T_{cl}^{\ A_T} \eta^{A_T}$ $f_{ff,AC\_FS}^{APU} = 0$ $if\ S_f^{FC\_AC} = cruise$ $f_{ff,ENG}^{A_T} = C_{fcr}^{A_T} T_{cr}^{A_T} \eta^{A_T}$ $T_{cr}^{A_T} = \begin{cases} D^{A_T} & \text{if } D^{A_T} < T_{cl}^{A_T} C_{Tcr}^{A_T} \\ T_{cl}^{A_T} C_{Tcr}^{A_T} & \text{if } D^{A_T} \geq T_{cl}^{A_T} C_{Tcr}^{A_T} \end{cases}$ $D^{A_T} = \frac{1}{2}\left(v_{TAS}^{A_T}\right)^2 S^{A_T} \rho \left[C_{D1}^{A_T} + C_{D2}^{A_T} \left(\frac{2g\left(m_{final}^{weight} - f_{burnt}\right)}{\left(v_{TAS}^{A_T}\right)^2 S^{A_T} \rho} \right)^2 \right]$ $if\ S_f^{FC\_AC} = descent$ if $h > h_{app}$

		$f_{ff,ENG}^{A_T} = C_{f3}^{A_T}\left(1 - \frac{h}{C_{f4}^{A_T}}\right)$ $if\ \ h \in \left(h_{ld}, h_{app}\right]$ $f_{ff,ENG}^{A_T} = C_{Tapp}^{A_T} T_{cl}^{A_T} \eta^{A_T}$ $if\ \ h \le h_{ld}$ $f_{ff,ENG}^{A_T} = C_{Tld}^{A_T} T_{cl}^{A_T} \eta^{A_T}$ Where: $\eta^{A_T} = C_{f1}^{A_T}\left(1 + \frac{v_{TAS}^{A_T}}{C_{f2}^{AT}}\right)$ $T_{cl}^{A_T} = C_{T1}^{A_T}\left(1 - \frac{h}{C_{T2}^{A_T}} + C_{T3}^{A_T} h^2\right)$ $\rho = \rho(h)$ Parameters used are described in the fuel consumption model Variables used from other LPNs: • $S_f^{FC\_AC}$ from FC_AC • Aircraft parameters from AC_CH • ρ from EN • m_{final}^{weight} from FC_PL
AC_FS_G3: AC_FS_P1 →AC_FS_P1	$t_{timerFS2} \le 0$	A token with colour AC_FS: $t_{timerFS2} = \Delta t_{timerFS2}$ $if\ \ f_{leacked} < Q_{\max} m_f^{FRF} : f_{leacked} = f_{AC\_HZ}^{loss} + f_{leacked}$ $f_{ff,AC\_FS}^{ENG} = f_{ff,ENG}^{AT} f_{factor,AC\_HZ}^{ENG} + f_{ff,ENG}^{AT} f_{factor,AC\_HZ}^{aerodyn} + f_{ff,ENG}^{AT} f_{factor,AC\_HZ}^{ICE} +$ $+ f_{ff,ENG}^{AT} f_{ff,AC\_HZ}^{inc}$ $f_f^{tot} = f_{ff,AC\_FS}^{ENG} + f_{ff,AC\_FS}^{APU} + f_{AC\_HZ}^{loss}$ Variables used from other LPNs: • $f_{ff,ICE}^{AT}, f_{factor}^{ENG}, f_{factor}^{AD}, f_{factor}^{ICE}, f_f^{inc}, f^{loss}$ from AC_HZ

Parameters

Parameters	**Description**	**Values**	**Explanation**
$\Delta t_{timerFS}$	time step in modelling nominal fuel consumption	$60s$	Minimum selectable time unit in the model
$\Delta t_{timerFS2}$	time step in modelling non-nominal fuel consumption	$60s$	Minimum selectable time unit in the model
$Q_{\max}$	parameter for maximum fuel	4	An assumption made that only one

	quantity that can be leaked		independent tank of the aircraft may leak, determining the leaked amount of fuel to the equivalent of 2 hours of cruise flight (4 times the FRF)

Incoming arcs within the same agent

There are incoming arcs from AC_HZ

- AC_HZ may affect fuel consumption.

Outgoing arcs within the same agent

None.

Incoming arcs from other agents

- Fuel System receives parameters related to the flight progress from the FMS.
- AC_CH provides fuel related parameters of the aircraft.
- EN provides the parameters needed for the fuel flow calculation.
- AC_HZ provides fuel-related factors.

Outgoing arcs to other agents

- FMS receives fuel-related information from the fuel system.

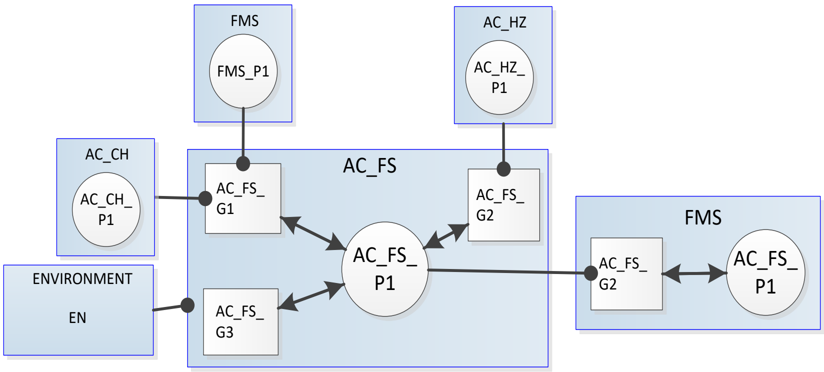

Figure 52 Aircraft FS LPN with its interactions

Fuel consumption model

Fuel flow f_f variable modelling is a multivariate process. In this section, we will demonstrate the variable’s calculation, based initially and extending the model introduced by [37], which was based on the Base of Aircraft Data v. 3.9 developed by Eurocontrol.

In total, there are two fuel consuming engines on the aeroplane; the propulsion engines and the Auxiliary Power Unit. In addition, pilots can engage systems such as the engines anti-ice or wing anti-ice system to prevent or counteract icing, leading to higher fuel consumption by the engines. Concerning the different flight phases, we may identify six different flight modes :(1) pre-flight (at the gate, not moving, APU is on, engines are off), (2) taxi, (3) climb, (4) cruise and (5) descent.

Variable	Notation	Unit
Fuel flow per phase of flight for the aircraft type A_T	$f_{ff,ENG}^{A_T}$	$kg \cdot s^{-1}$
Thrust value for the aircraft type A_T	$T_{cl}^{A_T}, T_{cr}^{A_T}, T_{app}^{A_T}, T_{ld}^{A_T}$	N
thrust specific fuel consumption for the aircraft type A_T	η_{AT}	$kg \cdot s^{-1} \cdot N^{-1}$
Drag for the aircraft type A_T	D_{A_T}	N
Current weight of the aircraft for the aircraft type A_T	$m_{final}^{weight} - f_{burnt}$	kg
air density	ρ	$kg \cdot m^{-3}$
true airspeed for the aircraft type A_T	$v_{TAS}^{A_T}$	$m \cdot s^{-1}$
Altitude	h	m

APU fuel flow

During pre-flight procedures (e.g. during boarding), GPU or APU provides power and bleed air to the aeroplane. In the case that APU is being used, there is small but considerable fuel consumption. Assuming a constant fuel flow:

$$f_f^{APU} = C_{APU}^{A_T}$$

Taxi fuel flow

Assuming a constant fuel flow during taxiing:

$$f_f^{taxi} = C_{tx}^{A_T}$$

Climb fuel flow

$$f_f^{cl}(h, v) = T_{cl} \cdot \eta(v)$$

$$T_{cl} = C_{T1} \cdot \left(1 - \frac{h}{C_{T2}} + C_{T3} h^2\right)$$

Cruise fuel flow

The thrust during the cruise phase, under normal conditions, is equal to drag. An upper limit is imposed to thrust value.

$$f_f^{cr}(h, v, m) = C_{fcr}^{A_T} \cdot T_{cr}^{A_T} \cdot \eta_{AT}(v)$$

$$T_{cr}^{A_T} = \begin{cases} D_{A_T} & \text{if} \quad D_{A_T} < T_{cl}^{A_T} \cdot C_{Tcr}^{A_T} \\ T_{cl}^{A_T} \cdot C_{Tcr}^{A_T} & \text{if} \quad D_{A_T} \geq T_{cl}^{A_T} \cdot C_{Tcr}^{A_T} \end{cases}$$

$$D = \frac{1}{2}\left(v_{A_T}^{TAS}\right)^2 S^{A_T} \rho(h) \cdot \left[C_{D1}^{A_T} + C_{D2}^{A_T} \cdot \left(\frac{2g\left(m_{OEW}^{A_T} + m_{PL}^{A_T} + m_f\right)}{\left(v_{A_T}^{TAS}\right)^2 S^{A_T} \rho(h)} \right)^2 \right]$$

Idle thrust descent fuel flow

During idle thrust descent, the fuel flow depends on altitude. The aircraft is in idle thrust descent if the altitude satisfies the condition $h > h_{app}$.

$$f_f^{idle}(h) = C_{f3}^{A_T} \cdot \left(1 - \frac{h}{C_{f4}^{A_T}}\right)$$

Approach fuel flow

For altitude values $h \in \left(h_{ld}, h_{app}\right]$, the aircraft is in the approach phase. Thrust is calculated through climb thrust with the employment of a correction factor C_{Tapp}. Fuel flow is then determined using thrust specific fuel consumption $\eta(v)$.

$$f_f^{app}(h,v) = T_{app}^{A_T} \cdot \eta_{A_T}(v)$$
$$T_{app}^{A_T} = T_{cl}^{A_T} \cdot C_{Tapp}^{A_T}$$

Landing fuel flow

For altitude $h < h_{ld}$, the aircraft is in the landing phase. Thrust is calculated through climb thrust with the employment of a correction factor C_{Tapp}. Fuel flow is then determined using thrust specific fuel consumption $\eta(v)$.

$$f_f^{land}(h,v) = T_{ld}^{A_T} \cdot \eta_{A_T}(v)$$
$$T_{ld}^{A_T} = T_{cl}^{A_T} \cdot C_{Tld}^{A_T}$$

Descent fuel flow

The following function summarizes the fuel flow for the entire descent phase.

$$f_f^{de}(h,v) = \begin{cases} f_f^{idle}(h) & \text{if} \quad h > h_{app} \\ f_f^{app}(h,v) & \text{if} \quad h \in \left(h_{ld}, h_{app}\right] \\ f_f^{land}(h,v) & \text{if} \quad h \in \left[0, h_{ld}\right] \end{cases}$$

Aircraft State LPN (AC_ST)

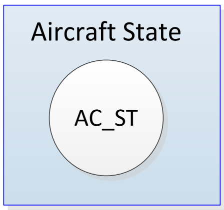

Figure 53 Aircraft State LPN

Colour type

Colour type	Notation	State Space	Description
AC_ST	P_x, P_y, P_z	$\mathbb{R}^+, \mathbb{R}^+, \mathbb{R}^+$	3D position of the aircraft
	P_V	$\mathbb{R}^+$	Airspeed of the aircraft

Colour function

Place	**Colour type**	**Colour function**
AC _ST_P1	A token with colour AC_ST	constant

Initial marking

Place	Initial Colour
AC _ST_P1	A token with colour AC_ST $P_x = 0$ $P_y = 0$ $P_z = 0$ $P_v = 0$

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

There is one arc to FMS

- FMS receives information about Aircraft position and airspeed.

Incoming arcs from other agents

There is one arc from EN

- Aircraft State receives spatial information from the Environment

Outgoing arcs to other agents

None

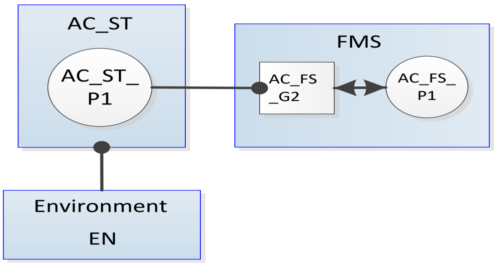

Figure 54 Aircraft State LPN

Aircraft Hazards LPN (AC_HZ)

Table 69 Aircraft Hazards LPN

Hazards group number	Hazards' serial numbers	Hazards group name	Modelled by the variable
AC_HZG_1	H21	Increased fuel consumption due to engines malfunction	f_{factor}^{ENG}
AC_HZG_2	H17, H18	Landing Gear malfunction	L_{LG}^{INOP}
AC_HZG_3	H24,H25,H26,H27	Degraded Aerodynamics	f_{factor}^{AD}
AC_HZG_4	H26	Icing (engines, wing)	f_{factor}^{ICE}

AC_HZG_5	H12 (H01,H02,H03),H05(H04), H08	Increased fuel consumption due to fuel system malfunction(s)	f_f^{inc}
AC_HZG_6	H10	Fuel leak	f^{leak}

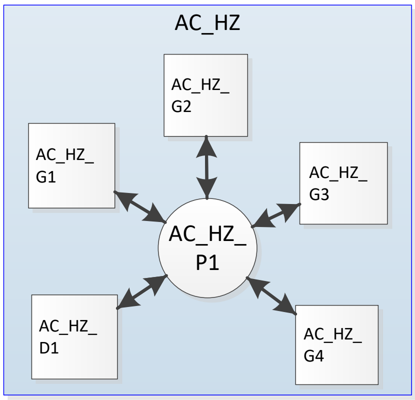

Figure 55 Aircraft Hazards LPN

Colour type

Colour type	Notation	State Space	Description
AC_HZ	f_{factor}^{ENG}	$\mathbb{R}^+$	Degraded engines factor
	f_{factor}^{ICE}	$\mathbb{R}^+$	Engines and wing anti-ice system operation additional consumption factor
	f_{factor}^{AD}	$\mathbb{R}^+$	Poor aerodynamics additional consumption factor
	$\mathrm{H}_{AC\_HZ}^{ICE}$	$\{true,\ false\}$	Ice accumulation on the structure. When this hazard is triggered, increased fuel consumption is expected due to the operation of the anti-ice system and (possibly) the poor aerodynamic characteristics
	L_{LG}^{INOP}	$\{true,\ false\}$	Landing gear extension system malfunctions. A landing gear malfunction will lead to a missed approach procedure, for the first only approach.
	f_f^{inc}	$\mathbb{R}_+$	additional fuel flow
	f^{leak}	$\mathbb{R}_+$	fuel loss rate
	t_{timer}^{ICE}	$\mathbb{R}_+$	timer for the icing information update

Colour function

Place	Colour type	Colour function
AC_HZ	A token with no colour	$dt_{timer}^{ICE} = -dt_{timer}^{ICE}$

Initial marking

Place	Initial Colour
AC _HZ	A token with colour AC_HZ $\mathrm{H}^{ICE} = false$ $L_{LG}^{INOP} = false$ $f_f^{inc} = 0$ $f^{leak} = 0$ $f_{factor}^{ICE} = 1$

Delay transitions

Transition	Delay rate	Firing function
AC_ HZ_D1: AC_HZ_P1→ AC_HZ_P1	Delay ~ Exp($\Delta t_{AC\_HZ\_D1}$)	A token with colour AC_ HZ: $f^{leak} \sim N(\mu_{f^{leak}}, \sigma_{f^{leak}}, l_{f^{leak}}, u_{f^{leak}})$

Guard transitions

Transition	Firing Condition	Firing function
AC_HZ_ G1: AC _HZ_P1→AC _HZ_P1	$F_{AC\_EV}^{S} = -1$	A token with colour AC_HZ: $f_{factor}^{ENG} \sim N(\mu_f^{ENG}, \sigma_f^{ENG}, l_f^{ENG}, u_f^{ENG})$, with probability P_{mal}^{ENG} $f_{factor}^{ENG} = f_{nom}^{ENG}$, with probability 1-$P_{mal}^{ENG}$ $f_{factor}^{AD} \sim N(\mu_f^{AD}, \sigma_f^{AD}, l_f^{AD}, u_f^{AD})$, with probability P^{AD} $f_{factor}^{AD} = f_{nom}^{AD}$, with probability 1-$P^{AD}$
AC_HZ_G2: AC_HZ_P1→ AC_HZ_P1	$t_{timer}^{ICE} \leq 0$	A token with colour AC_SS: $t_{timer}^{ICE} = \Delta t_{timer}^{ICE}$ $if\ \mathrm{H}_{AC\_HZ}^{ICE} = true: f_{factor}^{ICE} = N(\mu_f^{ice}, \sigma_f^{ice}, l_f^{ice}, u_f^{ice})$ $if\ \mathrm{H}_{AC\_HZ}^{ICE} = false: f_{factor}^{ICE} = 0$
AC_HZ_G3: AC_HZ_P1→AC _HZ_P1	$F_{AC\_EV}^{S} = 4$	A token with colour AC_HZ: $L_{LG}^{INOP} = true$, with probability P_{LG}^{Fail} $L_{LG}^{INOP} = false$, with probability 1- P_{LG}^{Fail}
AC_HZ_G4: AC_HZ_P1→AC _HZ_P1	$F_{AC\_EV}^{S} = 3$	A token with colour AC_HZ: $f_f^{inc} \sim N(\mu_{f^{inc}}, \sigma_{f^{inc}}, l_{f^{inc}}, u_{f^{inc}})$, with probability P_f^{inc} $f_f^{inc} = 1$, with probability 1- P_f^{inc}

Parameters

Parameters	**Description**	**Value**	**Explanation**
p^{leak}	Probability of fuel leakage f^{loss}	10^{-7}	H02: According to [2], there were 10 incidents related to a fuel leak in the USA in the period 2009-2018; consequently, we may assume a frequency, or 1/9.3 million flights [3]. Thus, we

			may assume a fuel leakage event in the area of 10^{-7}. As we have set the maximum leakage time to be of approximately 2 hours, we may assume an average of 1 hour. Then: $p^{leak}=10^{-7}$ $\mu_{non}^{leak}=3600s$ $\Delta\mathrm{t}_{\mathrm{AC\_HZ\_}D1}=\mu_{non}^{leak}\frac{1-p^{leak}}{p^{leak}}=35999996400s$
$\mu_{f^{loss}},\sigma_{f^{loss}},$ $\min_{f^{loss}},\max_{f^{loss}}$	Truncated normal distribution parameters of fuel leak rate	$0.4, 0.2,$ $0.2, 0.6$ $kg\cdot s^{-1}$	We assume a mean of 0.4kg per second fuel leak rate and a maximum of 0.6kg per second.
P_{LG}^{Fail}	Probability of landing gear extension system failure, under the condition that the manual system can be successfully used. (AC_HZG_2)	10^{-5}	Assuming that the landing gear manual extension system will be available, this failure is assumed to be categorized as “improbable/extremely remote “and thus we assume to lie in the area of 10^{-5} flights.
P_{mal}^{ENG}	Probability of unexpected higher engines fuel consumption due to hazards grouped in AC_HZG_1	10^{-4}	Assuming that this condition is assumed to be categorized as “remote” we assume it lies in the area of 10^{-4} flights.
f_{nom}^{ENG}	Nominal fuel consumption factor	1	
$\mu_f^{ENG},\sigma_f^{ENG},$ l_f^{ENG},u_f^{ENG}	Truncated normal distribution characteristics of the engine increased consumption factor	$1.2,\ 0.2,$ $1.1,\ 1.3$	We assume a mean of 20% increased consumption and a maximum of 30%.
P^{AD}	The probability that the aircraft has degraded aerodynamic characteristics, modelling AC_HZG_3	10^{-4}	Assuming that this condition is assumed to be categorized as “remote” we assume it lies in the area of 10^{-4} flights.
$\mu_f^{AD},\sigma_f^{AD},$ l_f^{AD},u_f^{AD}	Truncated normal distribution characteristics of the	$1.2,\ 0.2,$ $1.1,\ 1.3$	We assume a mean of 20% increased consumption and a maximum of 30%.

	aerodynamic deterioration factor		
f_{nom}^{AD}	Nominal aerodynamics factor	1	
P_f^{inc}	Probability of unexpected higher engines fuel consumption due to hazards grouped in AC_HZG_5	0.000012	H02: We assume that it is a mechanical failure of minor severity, and as such it should not happen more frequently than 10^{-5}. H05: We assume that it is a mechanical failure of major severity, and as such it should not happen more frequently than 10^{-6} . H08: [1] As it characterized as a rare event, we assume it should not happen more frequently than 10^{-6} Overall, $P_f^{inc} = 10^{-6} + 10^{-6} + 10^{-5} = 0.000012$
$\mu_{f^{inc}}, \sigma_{f^{inc}},$ $l_{f^{inc}}, u_{f^{inc}}$	Truncated normal distribution parameters of the increased consumption factor hazards	$1.15, 0.02,$ $1.1, 1.25$	We assume a fuel increase following a normal truncated distribution
$\mu_f^{ice}, \sigma_f^{ice},$ l_f^{ice}, u_f^{ice}	Truncated normal distribution parameters of the increased consumption factor due to ice accumulation	$1.15, 0.02,$ $1.1, 1.25$	We assume a fuel increase following a normal truncated distribution (mean value source[4])

[1] https://www.skybrary.aero/index.php/Fuel_Contamination

[2] https://www.ntsb.gov/_layouts/ntsb.aviation/index.aspx

[3]https://www.transtats.bts.gov/TRAFFIC/

[4] Airbus 320 FCOM

Incoming arcs within the same agent.

There is one incoming arc from AC_IC

- AC_IC provides information about ice accumulation on the aircraft surface or engines.

Outgoing arcs within the same agent

There is one arc to AC_FS

- AC_HZ provides to AC_FS the fuel consumption factors values if hazards are triggered.

Incoming arcs from other agents

None.

Outgoing arcs to other agents

- MRO agent receives information about the Engine consumption (deterioration) factor f_{factor}^{ENG}.

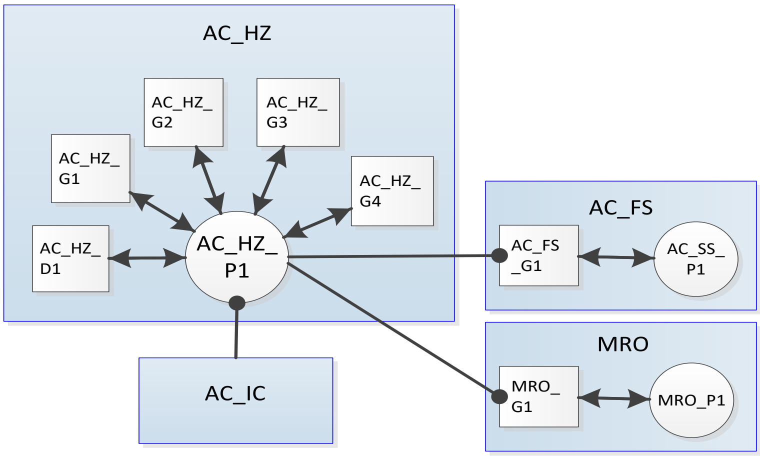

Figure 56 Aircraft hazards LPN and interactions

Aircraft Icing LPN (AC_IC)

- AC_ICE_T_ Nominal condition, Icing hazard is not triggered
- AP_P_HG6T: Non-nominal conditions, Icing hazard is triggered

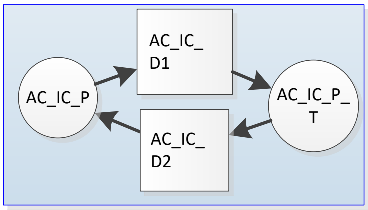

Figure 57 Aircraft Icing LPN

Colour type

Colour type	**Notation**	**State Space**	**Description**
AC_IC	$\mathrm{H}_{HZ\_IC}^{ICE}$	$\{true,\ false\}$	Icing is forming on the structure

Colour function

Place	**Colour type**	**Colour function**
AC _IC_ P	A token with colour AC_IC	constant
AC _IC P_T	No token	No colour

Initial marking

Place	Initial Colour
AC _IC	A token with colour AC_HZ $\mathrm{H}^{ICE} = false$

Delay transitions

Transition	Delay rate	Firing function

AC _IC _ D1: AC _IC_ P → AC _IC_P_T	Delay ~ Exp($\Delta t_{AC\_IC\_D1}$)	A token with colour AC_HZ $H^{ICE}_{HZ\_IC} = true$
AC _IC _ D2: AC _IC_P_T → AC _IC_ P	Delay ~ Exp($\Delta t_{AC\_IC\_D2}$)	A token with colour AC_HZ $H^{ICE}_{HZ\_IC} = false$

Parameters

Parameters	Description	Value	Explanation
p^{ice}_{non}	Probability of icing	0.0001	We defined the event “light or medium identified flying into icing condition”. As this event is of minor severity, as it can be resolved with airborne anti-ice equipment, we assume that it should not happen more frequently than 10^{-4}. $p^{ice}_{non} = 0.0001$ $\Delta t_{AC\_IC\_D1} = \mu^{ice}_{non} \frac{1 - p^{ice}_{non}}{p^{ice}_{non}} = 17998200s$ $\Delta t_{AC\_IC\_D2} = \mu^{ice}_{non} = 1800s$
μ^{ice}_{non}	Mean time of icing condition encounter	$1800s$	We also assume as 30 minutes the mean time where the aircraft may encounter in-flight icing condition.

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

There are to arcs to AC_HZ

- Information about the icing formation on the fuselage or engines is transferred to AC_HZ

Incoming arcs from other agents

None.

Outgoing arcs to other agents

None

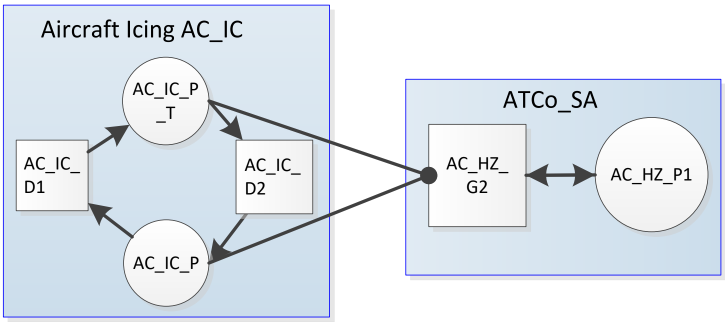

Figure 58 Aircraft Icing LPN

D.6 Airline’s Dispatch (AD)

Assumptions

1. Dispatchers account fuel for the en-route wind, but not for forecasted weather phenomena at airports or for other reasons (engines increased consumption, operational delays etc.).

Airline’ s Dispatch (AD)

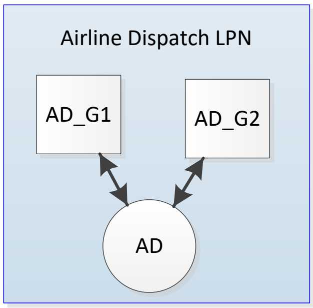

Figure 59 Airlines Dispatching LPN

Colour type

Colour type	Notation	State Space	Description
AD	**Route planning variables**		
	I_{AD}^{DEP}	N_{AP}	index of the departure airport
	I_{AD}^{ARR}	N_{AP}	index of the destination airport
	I_{AD}^{ALT}	N_{AP}	index of the alternate airport
	$W_{AD}^{j} = \begin{pmatrix} W_{ADx}^{j} \\ W_{ADy}^{j} \end{pmatrix}$	$\mathbb{R}^2$	Waypoints that form the route of the aircraft
	N_{W}^{AD}	$\mathbb{Z}$	number of waypoints
	$H_{cr,AD}^{opt}$	$\mathbb{R}_+$	planned (optimum) cruising altitude
	D_{total}^{AD}	$\mathbb{R}_+$	planned trip distance (from I_{DEP} to I_{ARR})
	D_{alt}^{AD}	$\mathbb{R}_+$	Alternate trip distance (from I_{ARR} to I_{ALT})
	T_{total}^{AD}	$\mathbb{R}_+$	planned trip time
	Fuel planning variables		
	$m_{f,AD}^{taxi}$	$\mathbb{R}_+$	planned taxi fuel
	$m_{f,AD}^{trip}$	$\mathbb{R}_+$	planned trip fuel
	$m_{f,AD}^{cont}$	$\mathbb{R}_+$	planned contingency fuel
	$m_{f,AD}^{altn}$	$\mathbb{R}_+$	planned alternate fuel
	$m_{f,AD}^{FRF}$	$\mathbb{R}_+$	planned final reserve fuel
	$m_{PL,AD}^{AT}$	$\mathbb{R}_+$	Mass of the aircraft’s payload

	m_{GW}^{AD}	$\mathbb{R}_+$	Estimation of the aircraft's gross weight by the dispatchers
	$m_{f,AD}^{AT}$	$\mathbb{R}_+$	Fuel uplift suggestion by the dispatchers

Colour function

Place	**Colour type**	**Colour function**
AD	A token with colour AD	constant

Initial marking

Place	Initial Colour
AD	A token with colour AD $I_{AD}^{DEP} = random\ i \in I$ $I_{AD}^{ARR} = random\ i \in I$ $I_{AD}^{ALT} = nearest\ i$ to I_{AD}^{ARR} $AT \in [0,7]$

Guard transitions

Transition	Guard condition	Firing function
AD _G1: AD _G1→ AD _G1	$F_{AC\_EV}^{S} = -1$	A token with colour AD Variables $W_{AD}^{j}, N_{W}^{AD}, D_{total}$ are calculated, as described in the route planning section below
AD _G2: AD _G2→ AD _G2	$F_{AC\_EV}^{S} = -1$	A token with colour AD Variables $H_{cr,opt}, m_f^{taxi}, m_f^{trip}, m_f^{cont}\ m_f^{alt}, m_f^{FRF}, T_{total}$ $m_{f,d}^{AD}, m_{f,t}^{AD}, N_{f,d}^{AD}, N_{f,t}^{AD}$ are calculated, as described in the fuel planning section below

Parameters

Parameters	**Description**	**Value**	**Explanation**
C_{H1}^{AT}	A matrix containing optimal altitude coefficient (No 1) per aircraft type	As shown in the table Parameters values below	[39]
C_{H2}^{AT}	A matrix containing optimal altitude coefficient (No 2) per aircraft type	As shown in the table Parameters values below	[39]
H_{max}^{AT}	maximal cruising altitude per aircraft type	As shown in the table Parameters values below	[39]
m_{OEW}^{AT}	A matrix containing the values of the aircraft's mass Operating Empty Weight(OEW) per aircraft type	As shown in the table Parameters values below	[39]
m_{PL}^{AT}	A matrix containing the values of the expected payload for the specific flight, per aircraft type	As shown in the table Parameters	[39]

		values below	
$H_{cr}^{1500\,ft}$	altitude used in computing contingency and FRF	$450\ m$	[1]
t_f^{cont}	time used in computing contingency	$300\ s$	[1]
t_f^{FRF}	time used in computing FRF	$1800\ s$	[1]

[1]Annex 6 of the International Civil Aviation Organisation (ICAO) Standards and Recommended Practices (SARPS).

Parameters values

Parameters values per aircraft type	$C_{H1}^{AT}\ m \cdot kg^{-1}$	$C_{H2}^{AT}\ m$	$H_{max}^{AT}\ m$	$m_{OEW}^{AT}\ kg$	Maximum take-off weight kg	Explanation
B737	0.0822	-16.489	12490	41150	78300	Source: Eurocontrol BADA 3.14
A320	0.1318	-95.580	12496	39000	77000	
A330	0.0323	-39.593	12496	125100	212000	
B787	0.0190	-43.098	13130	138000	250830	
A350	0.0276	-102.620	13130	146600	275000	

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

None.

Incoming arcs from other agents

There are incoming arcs from Met Office, Aircraft Characteristics and Airport Characteristics

- Met office provides information about the en-route and airport weather.
- Aircraft Characteristics provides fuel consumption information.
- Airport Characteristics provides the position and taxi times of the airports.

Outgoing arcs to other agents

There is one outgoing arc to Flight Crew planning

- Flight crew PL receives the flight plan and the suggested fuel plan.

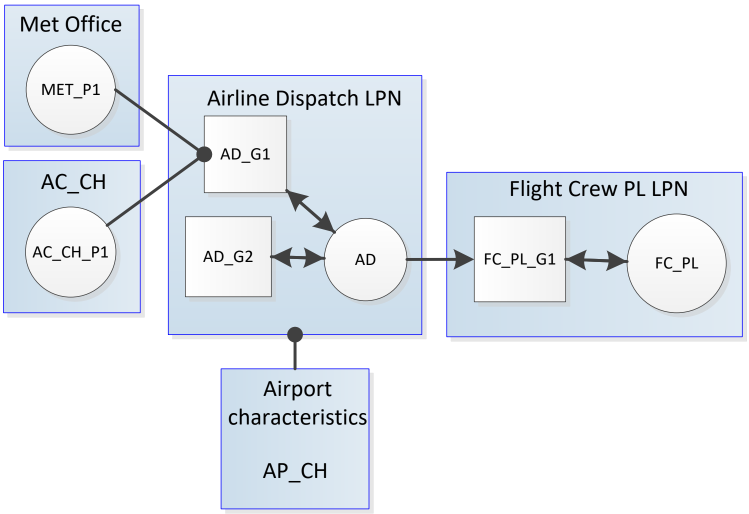

Figure 60 Airline's Dispatch LPN and interactions

Flight planning

Assumptions

- The airspace is considered entirely available during the Dispatch agent flight planning process. Any diversions due to airspace restrictions or severe weather are calculated and executed by the flight crew during the flight.

The foremost function of the airlines' dispatching office is to create flight plans for the airlines' flights. Flight planning and fuel planning are two separate but connected processes. In this section it will be explained how the flight planning and fuel planning processes are performed by the airline's dispatchers. It is of importance to mention that, concerning weather, dispatchers do not consider the weather phenomena taking place at the airports, but only the (en-route) wind.

In this model, flight planning consists of the computation of the variables W_{AD}^{j}, N_{W}^{AD} and D_{total}
We will use the following variables:

- $I_{DEP}, I_{ARR}, I_{ALT}$, A_T
- $n_{1,A}^{i}, m_{1,A}^{i}, d_{\sec}^{S_1}$ For $i \in \{I_{DEP}, I_{ARR}, I_{ALT}\}$ from AP agent.

The matrix W_{AD}^{j} comprises the route's waypoints. Variable N_{W}^{AD} is the total number of the route's waypoints, D_{total} is the length of the route. First, we start with the presentation of the calculation of the variable W_{AD}^{j}. Initially, the algorithm starts from the airport of departure and step by step goes forward one small sector distance (d_{sec}^{1}) at a time, until the arrival airport is reached. For example, for $I_{DEP} = (10,18)$ and $I_{ARR} = (17,22)$, the following initial route will be constructed: (10,18),(11,18) ,(12,18) ,(13,18) ,(14,18) ,(15,18) ,(16,18) ,(17,18) ,(17,19) ,(17,20) ,(17,21) ,(17,22)

Simulation of the SID and START procedures

After the creation on the initial route, the algorithm adds 2 fixes (x, y) in the very first part of the route, to simulate the SID procedure, and similarly, another two fixes at the end of the route, to simulate the STAR procedure, as follows:
(10,18), **(10,18.3) (11,18.3),** ((11,18) ,(12,18) ,(13,18) ,(14,18) ,(15,18) ,(16,18) ,(17,18) ,(17,19) , (17,20), ,(17,21), **(17.2,21),(17.2,22)**,(17,22)

The following illustration demonstrates the simulation of the SID procedure. Despite the route's waypoints are the red square dots, the aircraft first will fly to the green ones, adding a distance of 24km to the route. Exactly the same procedure is followed during approach (STAR), adding though another 50km to the total route.

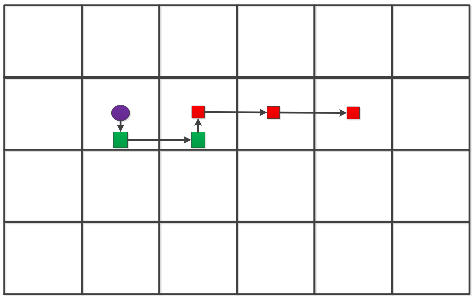

Figure 61 SID procedure simulation

Finally, the route is saved to the matrix W_{AD}^{j}. Variables N_W^{AD} and D_{total} are trivially computed as long as the route is determined. The same algorithm is employed to determine the route from the destination airport to the alternate.

Fuel planning

Assumption:

- We assume that all flight routes are long enough, that descent phase should start before the climb phase is finished. In other words, there is always a cruise phase in every flight.

In this section, it is described how the variables $H_{cr}^{opt}, m_f^{taxi}, m_f^{taxi}, m_f^{trip}, m_f^{cont}, m_f^{altn}, m_f^{FRF}, T_{total}, m_{f,d}^{AD}, m_{f,d}^{AD}, m_{f,t}^{AD}, N_{f,d}^{AD}, N_{f,t}^{AD}$ and function $d_{de,h}$ are computed. The following variables will be used:

- $W_{AD}^{j}, N_W^{AD}, D_{total}, D_{altn}, C_{H1}^{AT}, C_{H2}^{AT}, H_{MAX}^{AT}, m_{f,est}^{AT}, I_{DEP}, I_{ARR}, I_{ALT}$ from AD
- $M_{ws,xMET}^{n_2,m_2,t,h}, M_{ws,y,MET}^{n_2,m_2,t,h}, \rho$ from MET

- $t_{tx}^{I_{DEP}}, t_{tx}^{I_{ARR}}$ from AP
- $v_{TAS,cl}^{AT,h}, v_{TAS,cr}^{AT,h}, v_{TAS,de}^{AT,h}, v_{ROC}^{AT,h}, v_{ROD}^{AT,h}$ from AC_CH
- parameters related to fuel consumption from AC_CH and AC_FS

Airlines dispatch offices have in their possession dedicated advanced software, which can suggest fuel uplifts for specific flight routes. These suggestions are used by the dispatchers to make a fuel plan suggestion to the crew, which finally has the last word on the fuel uplift.

Calculating fuel intake also involves the knowledge of a good estimation of the aircraft mass, as the aircraft weight affects the fuel consumption, while in addition, aircraft's mass is a function of the fuel uplift. Moreover, aircraft mass is not known accurately, until a short amount of time before the flight initiation, as the dispatch can only make estimates about the weight of the useful payload (passenger plus cargo). Aircraft's gross weight (GW) m_{GW} is the total weight of the aircraft, and it is defined as $m_{GW} = m_{OEW}^{AT} + m_{PL}^{AT} + m_{f}^{AT}$, where:

- m_{OEW}^{AT}, is the Operating Empty Weight (OEW) of the aircraft. OEW is considered to be accurately known to the dispatch and crew before the flight.
- m_{PL}^{AT} (Payload) comprises passenger and cargo weight. This variable's value is known to the dispatch and crew with a small error.
- $m_{f,est}^{AD}$ is the total fuel uplift for the specific flight.

Before starting the calculation for the fuel uplift, a rough estimation of the aircraft's mass should be determined. This estimation is denoted as m_{GW}^{est}. Based on this estimate, we will find the optimum flight level H_{cr}^{opt} of the flight, which will render us able to start the fuel planning process.

Overall, summarizing the procedure that is followed in three steps:

1. Consider the reference gross weight of the aircraft, as provided in [39] and a reference altitude for the flight, which is 10500m for all cases; then, compute a first indicative fuel estimation, based on the aforementioned reference data and nominal airspeed (no wind is considered).
2. Compute a better estimation of the weight of the aircraft, using the above fuel estimation, as well as the optimum cruising altitude of the flight H_{cr}^{opt}.
3. Compute, finally, the actual fuel estimation $m_{f,est}^{AD}$ for the specific flight, considering the wind, the regulations and the fuel consumption and mass value per flight phase. Then, the final weight m_{GW} of the aircraft is corrected for the $m_{f,est}^{AD}$

Step 1

Variable $m_{f,est}^{AT}$ can initially be estimated roughly by summing the expected fuel quantities per flight phase.

$$m_{f,est}^{AD} = m_{f,est}^{taxi} + m_{f,est}^{trip} + m_{f,est}^{cont} + m_{f,est}^{altn} + m_{f,est}^{FRF}$$

$$m_{f,est}^{AD} = f_{f,taxi}^{A_T} \cdot \left(t_{tx}^{I_{DEP}} + t_{tx}^{I_{ARR}} \right) + \frac{D_{total}}{v_{cr,est,TAS}^{A_T}} \cdot f_{f,cr,est}^{A_T} + \frac{D_{total}}{v_{cr,est,TAS}^{A_T}} \cdot f_{f,fin,est}^{A_T} \cdot 5\% + \frac{D_{alt}}{v_{cr,est,TAS}^{A_T}} \cdot f_{f,fin,est}^{A_T} + f_{f,finalt,est}^{A_T} \cdot t_{f}^{FRF}$$

Where $f_{f,cr,est}^{AT}$ and $v_{cr,est,TAS}^{AT}$ are nominal fuel consumption and nominal true airspeed during the cruise phase of the aircraft type AT, $f_{f,fin,est}^{A_T}$ is the nominal fuel consumption for the expected weight at the time of the arrival at the destination airport and $f_{f,finalt,est}^{A_T}$ is the nominal fuel consumption for the expected weight at the time of the arrival at the alternate airport, as ICAO defines.

Step 2.

Now, we may calculate the value of the estimated mass of the aircraft for this route:

$$m_{GW}^{est} = m_{OEW}^{AT} + m_{PL}^{AT} + m_{f,est}^{AD}$$

Using the estimated weight m_{GW}^{est} we can determine the optimal cruising altitude:

$$H_{cr}^{opt} = \min\left\{H_{max}^{AT}, C_{H_1}^{AT} \cdot m_{GW}^{est} + C_{H_2}^{AT}\right\}$$

Step 3

For the calculations, we also need to calculate the direction of flight. The direction $s \in \mathbb{R}^2$ is a unit vector that describes the direction from a waypoint to the following:

$$s^{j \to j+1} = \frac{W_{AD}^{j+1} - W_{AD}^{j}}{\left|W_{AD}^{j+1} - W_{AD}^{j}\right|}$$

Additionally, we need the wind forecast from the Met service agent, analysed in components of x and y direction: $w_{x,MET}^{n_2,m_2,t,h}, w_{y,MET}^{n_2,m_2,t,h}$.

To calculate the fuel uplift of a specific flight, we first need to calculate the flight time for the three airborne flight phases, namely climb, cruise and descent.

Climb time and descent time calculation

Function $h_{cl,t}^{A_T}(t)$ determines the altitude that is gained in time t assuming the rate of climb is given by the function $v_{ROC}^{A_T}(h)$. It is computed as a solution of the ordinary differential equation.

$$\frac{d}{dt} h_{cl,t}^{A_T}(t) = v_{ROC}^{A_T}\left(h_{cl,t}^{A_T}(t)\right)$$
$$h_{cl,t}^{A_T}(0) = 0$$

Similarly, we define the function $h_{de,t}^{A_T}(t)$ using the rate of descent given by $v_{ROD}^{A_T}$.

$$\frac{d}{dt} h_{de,t}^{A_T}(t) = v_{ROD}^{A_T}\left(h_{de,t}^{A_T}(t)\right)$$
$$h_{de,t}^{A_T}(0) = 0$$

Now, we may calculate the time needed for climb and descent for each aircraft type as follows:

$$T_{cl}^{A_T} = \left(h_{cl,t}^{A_T}\right)^{-1}\left(H_{cr}^{opt}\right)$$
$$T_{de}^{AT} = \left(h_{de,t}^{A_T}\right)^{-1}\left(H_{cr}^{opt}\right)$$

Both $h_{cl,t}^{A_T}$ and $h_{de,t}^{A_T}$ depend only on each aircraft parameters, rendering possible to calculate in advance these function for each aircraft type and save them in the algorithm as a parameter, rendering us able to save valuable computation power and time.

Climb, cruise and descent distances calculation

Functions $d_{cl,t}^{A_T}$, $d_{cr,t}^{A_T}$ and $d_{de,t}^{A_T}$ represent the distance travelled in time t during climb, cruise and descent respectively, for the specific aircraft type A_T . Since only the true airspeed (TAS) is known, we need to take into consideration in our calculations the wind. The method that will be employed is the following:
First, we calculate the distances covered during climb and descent. These distances can also be called as the distance between the take-off point and the Top Of Climb (TOC) point, and the distance from the Top Of Descent (TOD) point to the touchdown point.

Where:

$$d_{cl,t}^{A_T}(t)=\int_0^t v_{cl,TAS}^{A_T}\left(h_{cl,t}^{A_T}(t)\right)du+\int_0^t\left\langle s^{0\to TOC}, w_{MET}^{n_2^{I_{DEP}},m_2^{I_{DEP}},0,h_{cl,t}^{A_T}(u)}\right\rangle du$$

$$d_{de,t}^{A_T}(t)=\int_0^t v_{de,TAS}^{A_T}\left(h_{de,t}^{A_T}(u)\right)du+\int_0^t\left\langle s^{TOD\to N^w}, w_{MET}^{n_2^{I_{ARR}},m_2^{I_{ARR}},T_{total}-T_{de}^{A_T},h_{de,t}^{A_T}(u)}\right\rangle du$$

For the calculation of $d_{cl,t}^{A_T}(t)$ and $d_{de,t}^{A_T}(t)$, the wind characteristics of the sector S_2 , in which the airport is located are considered. Similarly, during descent, the wind characteristics considered are those of the destination airport sector S_2 is located. Finally, we calculate the distance of the cruise phase (TOC to TOD):

$$D_{cr}^{A_T}=D_{total}-\left(D_{cl}^{A_T}+D_{de}^{A_T}\right)$$

Calculating the total time during the cruise phase is not trivial. As the environment's wind is different for each sector and each time point, it is needed to count for the aircraft position in the environment with respect to time. The following equations describe this process. First, we find the waypoint at which the TOC belongs:

$$j_{TOC}=[\frac{d_{cl}^{A_T}}{d_{\sec}^{S_1}}],$$

Wherewith [ ] we denote an upward rounding to the nearest (larger) integer.
As we know from previously, the matrix W_{AD}^{j} comprises the route's waypoint. Setting as the first waypoint of the cruise phase the waypoint of TOC j_{TOC} and as the last, the waypoint of TOD j_{TOD} , we can calculate the total time needed for the cruise phase of the flight.
The direction $s\in\mathbb{R}^2$ is a unit vector that describes the direction from a waypoint to the following:

$$s^{j\to j+1} = \frac{W_{AD}^{j+1} - W_{AD}^{j}}{\left|W_{AD}^{j+1} - W_{AD}^{j}\right|}$$

$$T_{cr} = \sum_{j=j_{TOC}}^{j_{TOD}} t_{cr,t}^{W_{AD}^{j}\to W_{AD}^{j+1}} = \sum \frac{d_{\sec}^{S_1}\sqrt{(n_1^{W_{AD}^{j+1}} - n_1^{W_{AD}^{j}})^2 + (m_1^{W_{AD}^{j+1}} - m_1^{W_{AD}^{j}})^2}}{v_{cr,TAS}^{AT,h=H_{crAO}^{AT}} + \left\langle s^{W_{AD}^{j}\to W_{AD}^{j+1}}, w_{MET}^{n_2^{W_{AD}^{j}}, m_2^{W_{AD}^{j}}, t_{cl}^{AT} + \sum_{k=TOC}^{j} t_{cr,t}^{W_{AD}^{j_{TOC}}\to W_{AD}^{j}}, H_{crAO}^{AT}} \right\rangle}$$

We can now compute finally the total flight's airborne time:

$$T_{total}^{A_T} = T_{cl}^{A_T} + T_{cr}^{A_T} + T_{de}^{A_T}$$

At this point, we have calculated the total distance D_{total} and the total time T_{total} of the flight route and hence, we are able to continue with the fuel planning phase.

Contingency fuel is equal to

$$m_f^{cont} = \max\left\{t_f^{cont} \cdot f_f^{cr}\left(h_{fAO}, v_{cr,TAS}^{AT}\left(h_{fAO}\right), m\right), 0.05 \cdot m_f^{trip}\right\}.$$

Final reserve fuel is calculated as

$$m_f^{FRF} = t_{fFR} \cdot f_f^{cr}\left(h_{fAO}, v_{cr}^{TAS}\left(h_{fAO}\right), m\right).$$

Taxi fuel is equal to

$$m_f^{taxi} = f_f^{taxi} \cdot \left(t_{tx}^{I_{DEP}} + t_{tx}^{I_{ARR}}\right).$$

As long as the above values are computed, the total fuel $m_{f,est}^{AD} = m_{f,est}^{taxi} + m_{f,est}^{trip} + m_{f,est}^{cont} + m_{f,est}^{altn} + m_{f,est}^{FRF}$ suggestion is provided to the Flight Crew agent.

Special operations flight planning

As presented in Chapter 2, special operations require special flight planning criteria to be fulfilled. As such, for executing special operations scenarios, the dispatch agent should take into consideration those criteria.

ETOPS

Simulating ETOPS flights is not trivial and some assumptions should be made:

- ETOPS flights require (as illustrated in Chapter 2) additional fuel to be taken, for the case of engine failure and/or depressurization. As such data are not provided by the database we used (BADA), these cases are not considered in ETOPS flights simulation. As such, we assume that a depressurization and/or an engine failure will not occur.

- Fuel for forecasted icing conditions: As Icing is not a forecastable weather variable in our model, we only consider non forecasted icing phenomena. As such, no extra fuel is considered for icing.
- Aircraft performance deterioration and MEL/CDL penalty are taken into consideration by MRO agent and provided to FC. As such, no intervention of the AD is needed.

D.7 Flight Crew (FC)

Assumptions

1. Flight and fuel planning by the crew may be sufficient (normal condition) or not (hazardous condition), as described by the variable P_{suf} .
2. During the flight planning, Flight crew considers the weather at the destination and alternate airport at the time of arrival to each one separately. If any of the 5 weather hazards groups of the AP_WX LPN are forecasted to affect the flight, an extra of 15-45 minutes of flying in cruising level is considered.
3. It is a common practice for pilots to round up the total fuel uplift to the nearest hundred or higher [40]. For example, for a desired fuel uplift of 11340kg, usually 11400kg will be requested. This common aviation fuel-safety practice is considered in our model and constitutes part of the discretionary (extra) fuel.
4. We assume that the situation awareness of the two members of the Flight Crew is always the same.

Flight Crew Planning LPN (FC_PL)

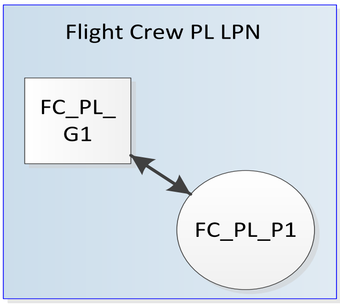

Figure 62 Flight Crew Planning LPN

Colour type

Colour type	Notation	State Space	Description
FC_PL	P_{suf}	$\{true, false\}$	Planning sufficiency: If $P_{suf} = true$ proper weather briefing is

			conducted and the crew will ask for extra fuel if needed. If $P_{suf} = false$, flight crew briefing is insufficient, and as such, an arbitrarily small amount of extra fuel is asked.
	m_{f,FC_PL}^{add}	$\mathbb{R}_+$	Additional (Extra) fuel amount, asked by the FC. This amount concerns compliance with a special type of flights or when extra fuel burn is expected, due to MEL/CDL or degraded engines (Modelled by the MRO agent variable $f_{factor,MRO}^{ENG}$)
	m_{f,FC_PL}^{extra}	$\mathbb{R}_+$	Discretionary fuel amount, asked by the FC.
	m_{f,FC_PL}^{TOTAL}	$\mathbb{R}_+$	Total fuel quantity asked by the FC to be uplifted.
	m_{final}^{weight}	$\mathbb{R}_+$	Final dispatched weight of the aircraft
	m_{f,FC_PL}^{extra1}	$\mathbb{R}_+$	The first part of the extra fuel: Amount of fuel needed due to the extra weight of any additional fuel taken by the pilots.
	m_{f,FC_PL}^{extra2}	$\mathbb{R}_+$	The second part of the extra fuel: Amount of fuel added for the rounding

Colour function

Place	**Colour type**	**Colour function**
FC_PL	FC_PL	constant

Initial marking

Place	Initial Colour
FC_PL_P1	A token with colour FC_PL $P_{suf} = \begin{Bmatrix} true, \text{ with probability 1-}P_{PS} \\ false, \text{ with probability } P_{PS} \end{Bmatrix}$ $m_{f,FC\_PL}^{add} = 0$ $m_{f,FC\_PL}^{extra} = 0$

Guard transitions

Transition	Guard condition	Firing function
FC_PL_G1: FC_PL_P1→FC_PL_P1	$F_{FC\_SA}^{S} = -1$	A token with colour FC_PL $if\ P_{suf} = true:$ $For\ t_{app}^{arr} = t_{tx,AP}^{I^{DEP}} + T_{cl} + T_{cr}, t_{app}^{alt} = t_{app}^{arr} + T_{de} + T_{cr}^{alt}:$ $If\ M_{AP,met}^{I_{arr},t_{app}^{arr}} = 1 \vee M_{AP,met}^{I_{alt},t_{app}^{alt}} = 1: m_{f,FC\_PL}^{add} = t_{AP}^{wx1} f_f^{AT,cruise}$ $(If\ M_{AP,met}^{I_{arr},t_{app}^{arr}} = 2 \vee M_{AP,met}^{I_{alt},t_{app}^{alt}} = 2) \vee$ $(If\ M_{AP,met}^{I_{arr},t_{app}^{arr}} = 3 \vee M_{AP,met}^{I_{alt},t_{app}^{alt}} = 3):$ $m_{f,FC\_PL}^{add} = t_{AP}^{wx2} f_f^{AT,cruise}$

		$(If\ \ M_{AP,met}^{I_{arr},t_{app}^{arr}}=4\vee M_{AP,met}^{I_{alt},t_{app}^{alt}}=4)\vee$ $(If\ \ M_{AP,met}^{I_{arr},t_{app}^{arr}}=5\vee M_{AP,met}^{I_{alt},t_{app}^{alt}}=5):$ $m_{f,FC\_PL}^{add}=t_{AP}^{wx3}\,f_{f}^{AT,cruise}$ $if\ \ P_{suf}\ =\ false:m_{f,FC\_PL}^{add}=0$ $if\ \ P_{suf}\ =true:$ $If\ f_{factor,MRO}^{ENG}>0:$ $m_{f,FC\_PL}^{add}=(m_{f,FC\_PL}^{add}+m_{f,AD}^{est})(1+f_{factor,MRO}^{ENG})$ $if\ \ P_{suf}\ =\ false:m_{f,FC\_PL}^{add}=0$ $if\ \ P_{suf}\ =true:$ $m_{f,FC\_PL}^{extra1}=\frac{(m_{f,AD}^{est}+m_{f,FC\_PL}^{add})}{1000}m_{factor,FC\_PL}^{extra1}$ $if\ \ P_{suf}\ =\ false:m_{f,FC\_PL}^{extra1}=0$ $if\ \ P_{suf}\ =true:m_{f,FC\_PL}^{extra2}=m_{round}^{suf}-(m_{f,AD}^{est}+m_{f,FC\_PL}^{extra1})\bmod(m_{round}^{suf})$ $if\ \ P_{suf}\ =\ false:m_{f,FC\_PL}^{extra2}=m_{round}^{notsuf}-(m_{f,AD}^{est})\bmod(m_{round}^{notsuf})$ $m_{f,FC\_PL}^{TOTAL}=m_{f,AD}^{est}+m_{f,FC\_PL}^{add}+m_{f,FC\_PL}^{extra1}+m_{f,FC\_PL}^{extra2}$ Used from other LPNs: • f_{factor}^{ENG} from MRO • $M_{AP,met}^{I_{arr},t}$, $M_{AP,met}^{I_{alt},t}$ from MET • $m_{f,AD}^{est}$ from AD

Parameters

Parameters	**Description**	**Value**	**Explanation**
P_{PS}	Probability of sufficiency in flight planning by the FC	0.9992	We assume that this event may occur either due to mistake or violation: Assuming that the probability of landing with less than FRF is in the order of magnitude of 10^{-5}, assuming that 80% of these events occurred due to flight planning mistake, we make the assumption that $10^{-5}\cdot 0.8=8\cdot 10^{-4}$,

			thus $P_{PS} = 1 - 8 \cdot 10^{-4} = 0.9992$
$m_{factor,FC\_PL}^{extra1}$	The factor for the computation of m_{f,FC_PL}^{extra1}. The product of the factor with every tone of additional fuel is, is the fuel penalty for carrying this extra tone of fuel; The factor is calculated through the nominal fuel consumption rates.	Aircraft specific, as shown in Table 70 below	Calculated through the fuel consumption model used.
m_{round}^{suf}	Rounding value of the fuel mass	$100\ kg$	[40]
m_{round}^{notsuf}	Rounding value of the fuel mass	$500\ kg$	Model assumption
t_{AP}^{wx1}	Mean expected duration of phenomena incurred by weather type 1	$600s$	Assumptions of section AP_WX used
t_{AP}^{wx2}	Mean expected duration of phenomena incurred by weather type 2	$1200s$	Assumptions of section AP_WX used
t_{AP}^{wx3}	Mean expected duration of phenomena incurred by weather type 3	$1800s$	Assumptions of section AP_WX used
t_{AP}^{wx4}	Mean expected duration of phenomena incurred by weather type 4	$2400s$	Assumptions of section AP_WX used
t_{AP}^{wx5}	Mean expected duration of phenomena incurred by weather type 5	$3600s$	Assumptions of section AP_WX used

Table 70 Fuel penalty factors

Aircraft Type	$m_{factor,FC\_PL}^{extra1}$ **value**
B737	0.043
A320	0.044
A330	0.055
B787	0.064
A350	0.069

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

There is one arc to FC_SA:

- FC_SA receives the flight planning information

Incoming arcs from other agents

There are three arcs to MET, AD and MRO agents:

- Met Office provides meteorological information to the flight crew.
- Airline's Dispatch office provides the flight plan on which is based the flight crew planning.
- MRO provides the crew with maintenance-related information (aircraft's technical log book).

Outgoing arcs to other agents

There are two arcs to ATCo_SA and GH:

- GH receives a fueling request by the Flight Crew (amount of fuel uplift).

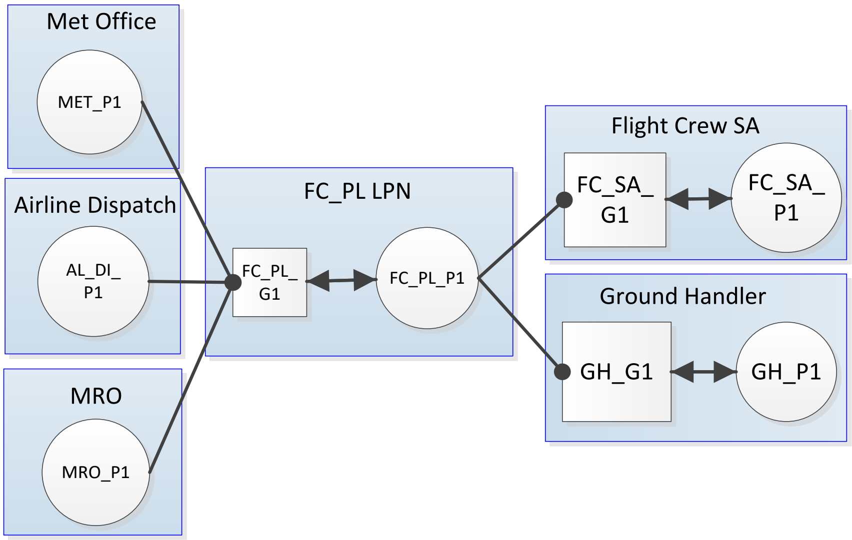

Figure 63 FC_PL agent and interactions

Flight Crew Situation Awareness (FC_SA)

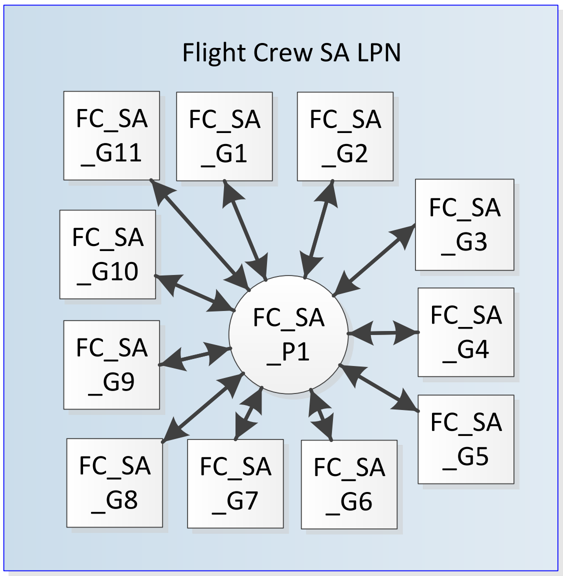

Figure 64 FC_SA LPN

Colour type

Colour type	Notation	State Space	Description
FC_SA	L_{qual}	$\{true, false\}$	Binary variable incorporating the hazards related to low-quality flight and fuel monitoring by the flight crew. $L_{qual} = true$ denotes a low quality of fuel monitoring and management.
	L_{div}	$\{true, false\}$	Binary variable denoting if a diversion is executed
	L_{ALERT}	$\{true, false\}$	Binary variable related to the amount of the remaining fuel. $L_{ALERT} = true$ denotes that the flight crew is aware that a fuel issue is ongoing, changing the rate of fuel monitoring to more frequent checks.
	1.FLIGHT PLAN		
	$W^j_{FC\_SA} = \begin{pmatrix} W^j_{x,FC\_SA} \\ W^j_{y,FC\_SA} \end{pmatrix}$	$\mathbb{R}^2$	waypoints of the current flight route
	$N_W^{FC\_SA}$	$\mathbb{Z}$	number of waypoints
	D_{total}	$\mathbb{R}_+$	planned trip distance
	T_{total}	$\mathbb{R}_+$	planned trip time
	$I^{ARR}_{FC\_SA}$	$\mathbb{Z}$	index of the destination airport
	$I^{ALT}_{FC\_SA}$	$\mathbb{Z}$	index of the alternate airport
	2.NOTAMS, WEATHER		

	$A_{NOTAM,FC\_SA}^{n_1,m_1,t}$	$\{true, false\}$	NOTAM update
	$M_{AP,FC\_SA}^{i,t}$	$\{0,1,2,3,4,5\}$	Airport weather update
	3.FUEL MONITORING AND MANAGEMENT		
	$m_f^{FC\_SA}$	$\mathbb{R}_+$	Current amount of fuel in tanks
	m_{f,FC_SA}^{dest}	$\mathbb{R}_+$	amount of fuel needed to get from current position to destination
	m_{f,FC_SA}^{alt}	$\mathbb{R}_+$	amount of fuel needed to get from the current position to the alternate airport
	m_{f,FC_SA}^{near}	$\mathbb{R}_+$	amount of fuel needed to get from the current position to the nearest airport
	m_{f,FC_SA}^{near2}	$\mathbb{R}_+$	amount of fuel needed to get from the current position to second nearest
	$m_{f,FC\_SA}^{del,dest}$	$\mathbb{R}_+$	amount of fuel that the crew computed as the amount needed for known delays at the destination airport
	$m_{f,FC\_SA}^{del,alt}$	$\mathbb{R}_+$	amount of fuel that crew computed as the amount needed for known delays at the alternate airport
	$m_{f,FC\_SA}^{del,near}$	$\mathbb{R}_+$	amount of fuel that crew computed as the amount needed for known delays at the nearest airport
	$m_{f,FC\_SA}^{del,near2}$	$\mathbb{R}_+$	amount of fuel that crew computed as the amount needed for known delays at the second nearest airport
	$FRF_{critical}$	$\{true, false\}$	FRF Critical (minimum fuel). The situation is triggered if it is identified that if no actions are taken, the aeroplane will possibly land with only the FRF
	$FE_{critical}$	$\{true, false\}$	Fuel Exhaustion Critical (emergency). The situation is triggered if it is identified by the FC that the fuel upon landing will be less than the FRF.
	4.SPATIAL AWARENESS-FLIGHT CHARACTERISTICS		
	x_{FC_SA}, y_{FC_SA}	$\mathbb{R}, \mathbb{R}$	coordinates that are identified as the position and the altitude of the aircraft by the crew
	$n_1^{x_{FC\_SA}}, m_1^{y_{FC\_SA}}$	$\mathbb{Z}^2$	Aircraft’s current position’s sector
	h_{FC_SA}	$\mathbb{R}_+$	Aircraft’s current altitude
	$v_{FC\_SA}^{TAS}$	$\mathbb{R}_+$	Aircraft’s current true airspeed
	$v_{FC\_SA}^{GS}$	$\mathbb{R}_+$	Aircraft’s current ground speed
	$v_h^{FC\_SA}$	$\mathbb{R}_+$	Aircraft’s current vertical speed
	5.TIME AWARENESS		

	T_{app}^{i}	$\mathbb{R}_{+}$	The time needed to initiate the descent (or approach) at airport i
	6.ATC CLEARANCES		
	$C_{clear,FC\_SA}^{startup}$	$\{true,\ false\}$	ATCo clearance for start-up, under the condition that $C_{FC\_SA}^{dep1}$ is true
	C_{clear,FC_SA}^{taxi}	$\{true,\ false\}$	ATCo clearance for taxi-out
	$C_{clear,FC\_SA}^{takeoff}$	$\{true,\ false\}$	ATCo clearance for take-off, under the condition that $C_{FC\_SA}^{dep2}$ is true.
	C_{clear,FC_SA}^{land}	$\{true,\ false\}$	ATCo clearance for landing
	$C_{FC\_SA}^{app}$	$\{true,\ false\}$	ATCo clearance for approach, considering operational delays
	$C_{FC\_SA}^{app2}$	$\{true,\ false\}$	ATCo clearance for approach, considering the weather
	$C_{FC\_SA}^{dep1}$	$\{true,\ false\}$	ATCo clearance for start-up, considering operational delays.
	$C_{FC\_SA}^{dep2}$	$\{true,\ false\}$	ATCo clearance for take-off, considering operational delays.
	7.Cabin Crew and GH		
	$C_{\sec,FC\_SA}^{land}$	$\{true,\ false\}$	Cabin security confirmation by CC before landing (true condition).
	$C_{\sec,FC\_SA}^{delay,to}$	$\{true,\ false\}$	Cabin security confirmation by CC before take-off (true condition).
	C_{GH}^{delay}	$\{true,\ false\}$	Ground handler’s confirmation that the handling procedure of the aircraft has finished (true condition).
	$C_{I_{DEP}}^{tx}$	$\{true,\ false\}$	Taxing procedure at departure airport has finished (true condition).
	$C_{I_{DEP}}^{tx}$	$\{true,\ false\}$	Taxing procedure at arrival airport has finished (true condition).
	8.Current flight phase		
	$F_{FC\_SA}^{s}$	$[-1,0,1,2,3,4,5,6,7,8,9]$	Flight phase, as perceived by the FC.

Colour function

Place	Colour type	Colour function
FC_SA_P1	FC_SA	$dt_{timer}^{progress} = -dt$ $dt_{FM}^{ALERT} = -dt$ $dt_{FM}^{1} = -dt$ $dt_{FM}^{2} = -dt$

		$dt_{timer,FC\_SA}^{wx,notam} = -dt$

Initial marking

Place	Initial Colour
FC_SA_P1	a token with colour FC_SA

Guard transitions

Transition	Guard condition	Firing function
FC_SA_G1: FC_SA _P1→ FC_SA _P1	$F_{FC\_SA}^{S} = -1$	A token with colour FC_SA: $I_{DEP}^{FC\_SA} = I_{DEP}^{AD}$ $I_{ARR}^{FC\_SA} = I_{ARR}^{AD}$ $I_{ALT}^{FC\_SA} = I_{ALT}^{AD}$ $W_{FC\_SA}^{j} = W_{AD}^{j}$ used variables from other LPNs: • $N_{W}^{AD}, I_{DEP}^{AD}, I_{ARR}^{AD}, I_{ALT}^{AD}, W_{AD}^{j}$ from AD
FC_SA_G2: FC_SA _P1→FC_SA _P1	$F_{FC\_SA}^{S} = 0$	$x_{FC\_SA} = W_{x,FC\_SA}^{0}$ $y_{FC\_SA} = W_{y,FC\_SA}^{0}$ $h_{FC\_SA} = 0$ $v_{h}^{FC\_SA} = 0$ $v_{GS}^{FC\_SA} = 0$ $v_{FC\_SA}^{TAS} = 0$
FC_SA_G3: FC_SA _P1→FC_SA _P1	$F_{FC\_SA}^{S} = 0$	A token with colour FC_SA: $L_{qual} = true$, with probability $P_{L}^{FC\_SA}$ $L_{qual} = false$, with probability $1\text{-}P_{L}^{FC\_SA}$
FC_SA_G4: FC_SA _P1→FC_SA _P1	$t_{timer}^{progress} \leq 0$	A token with colour FC_SA: $t_{timer}^{progress} = \Delta t_{timer}^{progress}$ $x_{FC\_SA} = x_{FMS}$ $y_{FC\_SA} = y_{FMS}$ $h_{FC\_SA} = h_{FMS}$ $v_{h}^{FC\_SA} = v_{h}^{FMS}$ $v_{FC\_SA}^{GS} = v_{FMS}^{GS}$ $v_{FC\_SA}^{TAS} = v_{FMS}^{TAS}$ $J_{FC\_SA}^{next} = J_{FMS}^{next}$ $W_{FC\_SA}^{j} = W_{ATCo\_AC}^{j}$ used variables from other LPNs: • $x_{FMS}, y_{FMS}, h_{FMS}, v_{h}^{FMS}, v_{FMS}^{GS}, v_{FMS}^{TAS}, J_{FMS}^{next}, s_{FMS}$ from FMS

		• $W^{j}_{ATCo\_AC,RV}$ from ATCo_AC • $F^{s}_{AC\_EV}$ from FC_EV
FC_SA_G5: FC_SA _P1→FC_SA _P1	$If\ F^{S}_{FC\_SA} > 2 \wedge F^{S}_{FC\_SA} < 7:$ $If\ L_{ALERT} = true: t^{ALERT}_{FM} \le 0$ $If\ L_{ALERT} = false:$ $If\ L_{qual} = true: t^{1}_{FM} \le 0$ $If\ L_{qual} = false: t^{2}_{FM} \le 0$	A token with colour FC_SA: $t^{ALERT}_{FM} = \Delta t^{ALERT}_{FM}$ $t^{1}_{FM} = \Delta t^{1}_{FM}$ $t^{2}_{FM} = \Delta t^{2}_{FM}$ *Expected delays fuel needs calculations:* 1.Due to $T^{i}_{app} = \frac{Dleft - D^{AT}_{de}}{v^{GS}_{FC\_SA}} + t_{now}, i = I_{arr}, I_{alt}, I_{near}, I_{near2}$ *For all* $i \in I_{arr}, I_{alt}, I_{near}, I_{near2}$ $if\ M^{i,t=T^{i}_{app}}_{AP,FC\_SA} = 0:\ m^{del,i}_{f,FC\_SA} = (t^{app,1}_{AP,i} + t^{app,4}_{AP,i})\, f^{AT}_{f,cruise}$ $if\ M^{i,t=T^{i}_{app}}_{AP,FC\_SA} = 1:\ m^{del,i}_{f,FC\_SA} = (t^{app,1}_{AP,i} + t^{app,4}_{AP,i} + T^{1}_{wx})\, f^{AT}_{f,cruise}$ $if\ M^{i,t=T^{i}_{app}}_{AP,FC\_SA} = 2 \vee M^{i,t=T^{i}_{app}}_{AP,FC\_SA} = 3:$ $m^{del,i}_{f,FC\_SA} = (t^{app,1}_{AP,i} + t^{app,4}_{AP,i} + T^{2,3}_{par})\, f^{AT}_{f,cruise}$ $if\ M^{i,t=T^{i}_{app}}_{AP,FC\_SA} = 4 \vee M^{i,t=T^{i}_{app}}_{AP,FC\_SA} = 5:$ $m^{del,i}_{f,FC\_SA} = (t^{app,1}_{AP,i} + t^{app,4}_{AP,i} + T^{4,5}_{par})\, f^{AT}_{f,cruise}$ *Fuel management decisions during approach/holding:* $If\ m^{dest}_{f,FMS} < Q_1 m^{FRF}_{f} + m^{del,Dest}_{f,FC\_SA} : L_{ALERT} = true$ $If\ m^{dest}_{f,FMS} < Q_2 m^{FRF}_{f} + m^{del,Dest}_{f,FC\_SA} :$ $FRF_{critical} = true$ $If\ m_{f} < Q_3 m^{FRF}_{f} + Q_4 m^{alt}_{f,FC\_SA} :$ $If\ m^{alt}_{f,FMS} > m^{FRF}_{f} + m^{del,alt}_{f,FC\_SA} : I_{arr} = I_{alt}, L_{div} = true$ $If\ m^{alt}_{f,FMS} > m^{FRF}_{f} + m^{del,alt}_{f,FC\_SA} : I_{arr} = I_{alt}, L_{div} = true$ $else\ if\ m^{near}_{f,FMS} > m^{FRF}_{f} + m^{del,near}_{f,FC\_SA} :$ $I_{arr} = I_{near}, L_{divert} = true$ $else\ if\ m^{near2}_{f,FMS} > m^{FRF}_{f} + m^{del,near2}_{f,FC\_SA} :$ $I_{arr} = I_{near2}, L_{div} = true$ *Fuel management decisions during the cruise:* $If\ m^{dest}_{f,FMS} < Q_5 m^{FRF}_{f} + m^{del,Dest}_{f,FC\_SA} : L_{ALERT} = true$ $If\ m^{dest}_{f,FMS} < Q_6 m^{FRF}_{f} + m^{del,Dest}_{f,FC\_SA} :$ $FRF_{critical} = true$

		$If\ m_f < Q_7 m_f^{FRF} + Q_8 m_{f,FC\_SA}^{alt}:$ $If\ m_{f,FMS}^{alt} > m_f^{FRF} + m_{f,FC\_SA}^{del,alt} : I_{arr} = I_{alt}, L_{div} = true$ $If\ m_{f,FMS}^{alt} > m_f^{FRF} + m_{f,FC\_SA}^{del,alt} : I_{arr} = I_{alt}, L_{div} = true$ $else\ if\ m_{f,FMS}^{near} > m_f^{FRF} + m_{f,FC\_SA}^{del,near}:$ $I_{arr} = I_{near}, L_{div} = true$ $else\ if\ m_{f,FMS}^{near2} > m_f^{FRF} + m_{f,FC\_SA}^{del,near2}:$ $I_{arr} = I_{near2}, L_{div} = true$ $If\ m_{f,FMS}^{dest} \leq m_f^{FRF} : FE_{critical} = true$ used variables from other LPNs: • m_f^{FRF} from AD • $m_{f,FMS}^{DEST}, d_{FMS}^{left,dest}, t_{FMS}^{left,dest}, dm_f^{FMS}, m_{f,FMS}^{alt}, m_{f,FMS}^{near}$ from FMS • $M_{AP,MET}^{i,t}, t_{AP,I_{ARR}}^{app,1}, t_{AP,I_{ARR}}^{app,4}$ from ATCo_AC • $f_{f,cruise}^{AT}$ from AC_CH
FC_SA_G6: FC_SA _P1→FC_SA_P1	$t_{timer,FC\_SA}^{wx,notam} \leq 0$	A token with colour FC_SA: $t_{timer,FC\_SA}^{wx,notam} = \Delta t_{timer,FC\_SA}^{wx,notam}$ $M_{AP,FC\_SA}^{i,t} = M_{AP,ATCo\_SA}^{i,t}$ Variables used from other LPNs: • $M_{AP,ATCo\_SA}^{i,t}$ from ATCo AC
FC_SA_G7: FC_SA _P1→FC_SA_P1	$F_{FC\_SA}^{S} = 1$	A token with colour FC_SA: $C_{\sec,FC\_SA}^{delay,to} = C_{\sec,CC}^{delay,to}$ Variables used from other LPNs: • $C_{\sec,CC}^{delay,to}$ from CC
FC_SA_G8: FC_SA _P1→FC_SA_P1	$F_{FC\_SA}^{S} = 4$	A token with colour FC_SA: $C_{\sec,FC\_SA}^{land} = C_{\sec,CC}^{land}$ Variables used from other LPNs: • $C_{\sec,CC}^{land}$ from CC
FC_SA_G9: FC_SA _P1→FC_SA_P1	$F_{FC\_SA}^{S} = 1 \vee F_{FC\_SA}^{S} = 4$	A token with colour FC_SA: $W_{FC\_SA}^{j} = W_{ATCo\_AC}^{j}$ Variables used from other LPNs: • $W_{ATCo\_AC}^{j}$ from ATCo_AC

FC_SA_G10: FC_SA_P1→FC_SA_P1	$F_{FC\_SA}^{S} = 0$	A token with colour FC_SA: $C_{GH}^{delay} = H_{GH}^{hadl}$ Variables used from other LPNs: • H_{GH}^{hadl} from GH
FC_SA_G11: FC_SA_P1→FC_SA_P1	$F_{FC\_SA}^{S} = -1 \vee F_{FC\_SA}^{S} = 0 \vee$ $F_{FC\_SA}^{S} = 1 \vee F_{FC\_SA}^{S} = 3 \vee F_{FC\_SA}^{S} = 4$	$C_{FC\_SA}^{app} = C_{ATCo\_AC}^{app}$ $C_{FC\_SA}^{app2} = C_{ATCo\_AC}^{app2}$ $C_{clear,FC\_SA}^{land} = C_{clear,ATCo\_AC}^{land}$ $C_{clear,FC\_SA}^{takeoff} = C_{clear,ATCo\_AC}^{takeoff}$ $C_{clear,FC\_SA}^{taxi} = C_{clear,ATCo\_AC}^{taxi}$ $C_{clear,FC\_SA}^{startup} = C_{clear,ATCo\_AC}^{startup}$ Variables used from other LPNs: • $C_{ATCo\_AC}^{app}$, $C_{ATCo\_AC}^{app2}$, $C_{clear,ATCo\_AC}^{land}$, $C_{clear,ATCo\_AC}^{takeoff}$, $C_{clear,ATCo\_AC}^{taxi}$ $C_{clear,ATCo\_AC}^{startup}$ from ATCo_AC

Parameters

Parameters	**Description**	**Value**	**Explanation**
Δt_{info}	the time interval between two information updates for normal SA	60 s	The minimum selectable time period
$P_{L}^{FC\_SA}$	probability of conformance with the regulated fuel monitoring practices	0.99999	We assume that this event may occur either due to a systematic mistake or violation. We also assume that this probability should be in the same order of magnitude as the probability P_{PS} estimated in FC_PL. Therefore, we assume $P_{L}^{FC\_SA} = 1 - 10^{-5} = 0.99999$
$t_{timerFC\_SA}$	timer for updating the information of the crew	60 s	The minimum selectable time period
t_{FM}^{1}	timer for Flight Monitoring (normal)	1800 s	[1]
t_{FM}^{2}	timer for Flight Monitoring (low)	3600 s	Assumption of double the time of the regulated value
t_{FM}^{ALERT}	timer for Flight Monitoring (alert)	60 s	The minimum selectable time period

$t^{wx,notam}_{timerFC\_SA}$	timer for weather and NOTAM information	1800 s	The METAR refreshing time period
$t^{progress}_{timerFC\_SA}$	timer for updating the information of the crew (progress)	60 s	The minimum selectable time period
t^{wx1}_{AP}	Mean expected duration of phenomena incurred by weather type 1	$600s$	Assumptions of Chapter AP_WX used
t^{wx2}_{AP}	Mean expected duration of phenomena incurred by weather type 2	$1200s$	Assumptions of Chapter AP_WX used
t^{wx3}_{AP}	Mean expected duration of phenomena incurred by weather type 3	$1800s$	Assumptions of Chapter AP_WX used
t^{wx4}_{AP}	Mean expected duration of phenomena incurred by weather type 4	$2400s$	Assumptions of Chapter AP_WX used
t^{wx5}_{AP}	Mean expected duration of phenomena incurred by weather type 5	$3600s$	Assumptions of Chapter AP_WX used
Q_1,Q_2,Q_3,Q_4 Q_5,Q_6,Q_7,Q_8	Parameters used in fuel management	1.5,1.3,1.1, 1.1,1.4,1.2, 1.1,1.1	Assumed model parameters

[1] https://safetyfirst.airbus.com/fuel-monitoring-on-a320-family-aircraft/

Incoming arcs within the same agent

There is one arc from FC_EV.

- FC_EV provides information about the current phase of flight.

Outgoing arcs within the same agent

There is one outgoing arc to FC_AC

- Flight Crew Actions act as an intermediator between FC_SA and FMS or ATCo_AC

Incoming arcs from other agents

There are 5 incoming arcs to Flight Crew Situation Awareness

- Flight crew updates its SA about the flight variables, aircraft’s systems status, fuel level (fuel level monitoring) through the FMS
- Flight Crew Planning sends all the flight planning information to the Flight Crew SA.
- Cabin Crew informs the Flight Crew that the cabin is secure for landing and take-off.
- ATCo_AC gives flight instructions and weather information to Flight Crew SA.
- GH provides FC_SA with information about the finishing of the handling services.

Outgoing arcs to other agents

None.

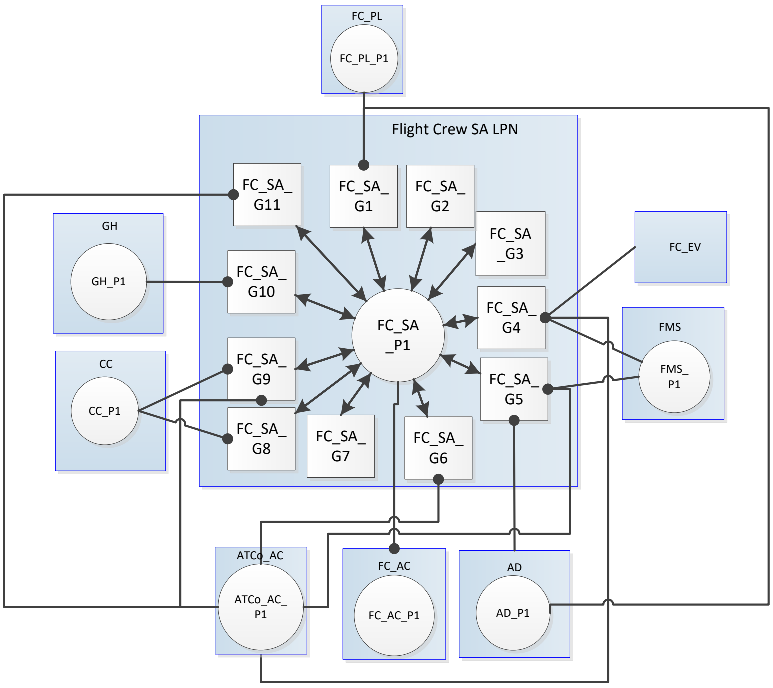

Figure 65 FC_SA interactions

Flight Evolution LPN (FC_EV)

Assumptions

- FC_EV includes the knowledge of the Flight Crew about the phase of flight. We assume that the Flight Crew's knowledge about the phase of the flights always coincides with the actual phase of the flight.

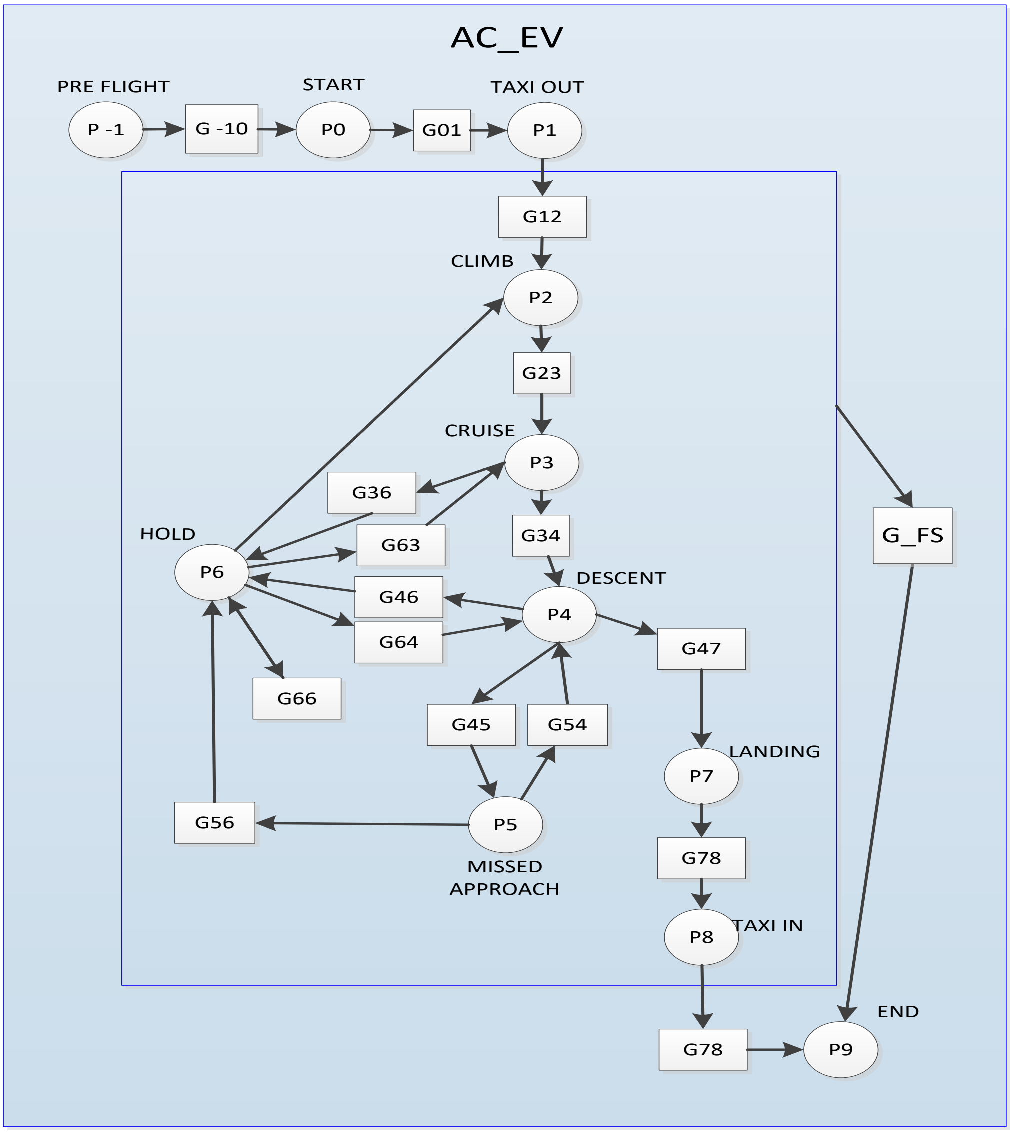

Figure 66 Flight Evolution FC_EV LPN. This LPN demonstrates the progress of the flight.

Colour type

Colour type	Notation	State Space	Description
	$H^{cr}_{FC\_EV}$	$\mathbb{R}$	Cruising altitude of the aircraft
	$d_{de,h}$	$\mathbb{R}$	Descent distance required
	$G^{missedAP}_{counter}$	$\mathbb{Z}$	Missed approach counter
	$F^{S}_{FC\_EV}$	$\{-1,0,1,2,3,$ $4,5,6,7,8,9\}$	Flight phase

Colour function

Place	Colour type	Colour function
FC_EV_P-1 Pre-flight	FC_EV	constant
FC_EV_P0 Start	FC_EV	constant

FC_EV_P1 Taxi-out	FC_EV	constant
FC_EV_P2 Climb	FC_EV	constant
FC_EV_P3 Cruise	FC_EV	constant
FC_EV_P4 Descent	FC_EV	constant
FC_EV_P5 Missed Approach	FC_EV	constant
FC_EV_P6 Hold	FC_EV	constant
FC_EV_P7 Landing	FC_EV	constant
FC_EV_P8 Taxi-in	FC_EV	constant
FC_EV_P9 End	FC_EV	constant

Initial marking

Place	Initial Colour
FC_EV_P-1	A token with colour FC_EV $F^{S}_{FC\_EV} = -1$ $G^{missedAPP}_{counter} = 0$
FC_EV_P0- FC_EV_P8	No token

Guard transitions

Transition	Firing condition	Firing function
FC_EV_G-10: Pre-flight → start FC_EV_P-1 → FC_EV_P0	$[F^{S}_{FC\_EV} = -1] \wedge [C^{dep2}_{FC\_SA} = true] \wedge$ $[C^{startup}_{clear,FC\_SA} = true]$	A token with colour FC_EV: $F^{S}_{FC\_EV} = 0$
FC_EV_G01: start → taxi out FC_EV_P0 → FC_EV_P1	$[F^{S}_{FC\_EV} = 0] \wedge [C^{taxi}_{clear,FC\_SA} = true] \wedge$ $[C^{delay}_{GH} = true]$	A token with colour FC_EV: $F^{S}_{FC\_EV} = 1$
FC_EV_G12: taxi out → climb FC_EV_P1 → FC_EV_P2	$[F^{S}_{FC\_EV} = 1] \wedge [C^{takeoff}_{FC\_SA} = true] \wedge$ $[C^{tx}_{I_{DEP}} = true] \wedge [C^{dep1}_{FC\_SA} = true] \wedge$ $[C^{delay,to}_{\sec,FC\_SA} = true]$	A token with colour FC_EV: $F^{S}_{FC\_EV} = 2$
FC_EV_G23: climb → cruise FC_EV_P2 → FC_EV_P3	$[F^{S}_{FC\_EV} = 2] \wedge [h_{FC\_SA} \geq H^{cr}_{FC\_SA}]$	A token with colour FC_EV: $F^{S}_{FC\_EV} = 3$
FC_EV_G34: cruise→ descent FC_EV_P3 → FC_EV_P4	$[F^{S}_{FC\_EV} = 3] \wedge [d^{left}_{FMS} \leq d^{AT}_{de,h,AD}]$	A token with colour FC_EV: $F^{S}_{FC\_EV} = 4$
FC_EV_G47: descent →landing FC_EV_P4 → FC_EV_P7	$[F^{S}_{FC\_EV} = 4] \wedge [h_{FC\_SA} \leq 0] \wedge$ $[C^{land}_{\sec,FC\_SA} = true] \wedge [C^{land}_{clear,FC\_SA} = true] \wedge$ $[C^{app1}_{ATCo\_AC} = true] \wedge [C^{app2}_{ATCo\_AC} = true]$	A token with colour FC_EV: $F^{S}_{FC\_EV} = 7$
FC_EV_G78: Landing → end (taxi/in)	$[F^{S}_{FC\_EV} = 7] \wedge [C^{tx}_{I_{ARR}} = true]$	A token with colour FC_EV: $F^{S}_{FC\_EV} = 8$

FC_EV_P7 → FC_EV_P8		
FC_EV_G45: descent → missed approach FC_EV_P4 → FC_EV_P5	$[F_{FC\_EV}^{S} = 4] \wedge [h \leq h_{MA}^{I_{ARR}}] \wedge$ $\{[(G_{counter}^{missedAPP} = 0) \wedge (C_{\sec,FC\_SA}^{land} = false)] \vee$ $[(G_{counter}^{missedAP} = 0) \wedge (L_{LG,AC\_HZ}^{INOP} = true)] \vee$ $[C_{clear,FC\_SA}^{land} = false] \vee [C_{ATCo\_AC}^{app2} = false]\}$	A token with colour FC_EV: $F_{FC\_EV}^{S} = 5$ $G_{counter}^{missedAPP} = G_{counter}^{missedAPP} + 1$
FC_EV_G54: missed approach → descent FC_EV_P5 → FC_EV_P4	$[F_{FC\_EV}^{S} = 5] \wedge [h \geq h_{hold}^{I_D}] \wedge$ $\{[C_{clear,FC\_SA}^{land} = true] \vee$ $[C_{ATCo\_AC}^{app1} = true] \vee [C_{ATCo\_AC}^{app2} = true]\}$	A token with colour FC_EV: $F_{FC\_EV}^{S} = 4$
FC_EV_G46: descent → hold FC_EV_P4 → FC_EV_P6	$[F_{FC\_EV}^{S} = 4] \wedge [C_{ATCo\_AC}^{app1} = false] \wedge$ $[C_{ATCo\_AC}^{app2} = false]$	A token with colour FC_EV: $F_{FC\_EV}^{S} = 6$
FC_EV_G64: hold→ descent FC_EV_P6 → FC_EV_P4	$[F_{FC\_EV}^{S} = 6] \wedge [C_{ATCo\_AC}^{app1} = true] \wedge$ $[C_{ATCo\_AC}^{app2} = true] \wedge [h \geq h_{hold}^{I_D}]$	A token with colour FC_EV: $F_{FC\_EV}^{S} = 4$
FC_EV_G56: Missed Approach → hold FC_EV_P5 → FC_EV_P6	$[F_{FC\_EV}^{S} = 5] \wedge \{[h \leq h_{hold}^{I_{ARR}}] \vee$ $[C_{\sec}^{land} = false] \vee [C_{ATCo\_AC}^{app1} = false] \vee$ $[C_{ATCo\_AC}^{app2} = false]\}$	A token with colour FC_EV: $F_{FC\_EV}^{S} = 6$
FC_EV_G62: hold → climb FC_EV_P6 → FC_EV_P2	$F_{FC\_EV}^{S} = 6 \wedge L_{div} = true$	A token with colour FC_EV: $F_{FC\_EV}^{S} = 2$ used variables from other LPNs: • L_{div} from FC_SA
FC_EV_G_FS: FC_EV_P2 → FC_EV_P9 FC_EV_P3 → FC_EV_P9 FC_EV_P4 → FC_EV_P9 FC_EV_P5 → FC_EV_P9 FC_EV_P6 → FC_EV_P9 FC_EV_P7 → FC_EV_P9 FC_EV_P8 → FC_EV_P9	$m_f \leq 0 \wedge F_{FC\_EV}^{S} > 2 \wedge F_{FC\_EV}^{S} < 7$	A token with colour FC_EV: $F_{FC\_EV}^{S} = 9$ used variables from other LPNs: • m_f from AC_FS

Incoming arcs within the same agent

There is one arc from FC_SA:

- Variables needed for the phase of flight changes are taken from FC_SA.

Outgoing arcs within the same agent

There are two arcs to FC_AC and FC_SA:

- When the phase of flight changes, FC_AC receives the information, to take actions to the FMS.
- FC_SA receives information about the current flight state.

Incoming arcs from other agents

None.

Outgoing arcs to other agents

None.

Flight Crew Actions LPN

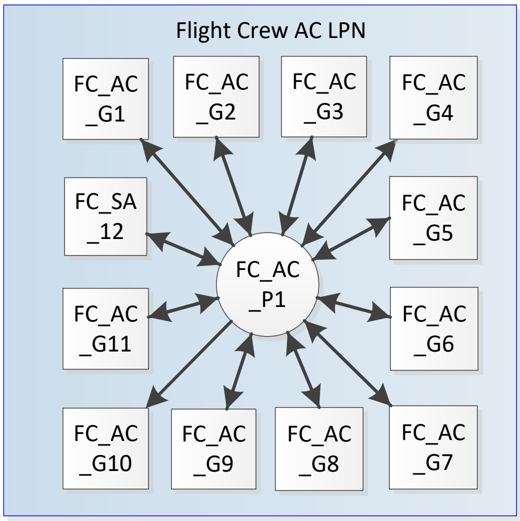

Figure 67 Flight Crew Actions FC_AC LPN

Colour type

Colour type	**Notation**	**State Space**	**Description**
FC_AC	$W^{j}_{FC\_AC}$	$\mathbb{R}^2$	Radar vectors instructions, as received from the ATCo Agent. (Waypoints of the route that forms the radar vectors)
	$I^{ARR}_{FC\_AC}$	$\mathbb{Z}$	Declaration of new destination airport (diversion)
	$FRF^{dec}_{critical}$	$\{true, false\}$	“Minimum fuel” declaration
	$FE^{dec}_{critical}$	$\{true, false\}$	“MAYDAY fuel” declaration
	$W^{j}_{FC\_AC}$	$\mathbb{R}^2$	Flight plan waypoints
	$S^{FC\_AC}_{f}$	$\{\text{ground,taxi,climb, cruise,descent}\}$	Fuel consumption phase of flight
	$v^{AT,TAS}_{FC\_AC}$	$\mathbb{R}$	Aircraft’s true airspeed
	$v^{h}_{FC\_AC}$	$\mathbb{R}$	Aircraft’s vertical speed
	L_{div}	$\{true, false\}$	Diversion Boolean variable, denoting if a diversion should be executed

Colour function

Place	**Colour type**	**Colour function**
FC_AC_P1	FC_AC	constant

Initial marking

Place	Initial Colour
FC_AC_P1	A token with colour FC_AC: $W^j_{FC\_AC} = \begin{pmatrix} W^j_{x,FC\_AC} \\ W^j_{y,FC\_AC} \end{pmatrix} = W^j_{FC\_SA}$

Guard transitions

Transition	Firing condition	Firing function
FC_AC_G1: FC_AC _P1→FC_AC _P1	$F^S_{FC\_EV} = 0$	A token with colour FC_AC: $W^j_{FC\_AC} = W^j_{AD}$ $J^{next}_{FC\_AC} = 1$ $v^{AT}_{h,_{FC\_AC}} = 0$ $S^{FC\_AC}_f = ground$ Variables used from other LPNs: • W^j_{AD} from AD
FC_AC_G2: FC_AC_P1-→ FC_AC_P1	$F^S_{FC\_EV} = 1$	A token with colour FC_AC: $S^{FC\_AC}_f = taxi$
FC_AC_G3: FC_AC _P1→FC_AC _P1	$F^S_{FC\_EV} = 2$	A token with colour FC_AC: $v^{AT,TAS}_{FC\_AC} = v^{AT,TAS}_{cl,AC\_CH}$ $v_{h,FC\_AC} = v^{AC\_CH}_{h,ROC}$ $S^{FC\_AC}_f = climb$ Variables used from other LPNs: • $v^{AT,TAS}_{cl,AC\_CH}$, $v^{AC\_CH}_{h,ROC}$ from AC_CH
FC_AC_G4: FC_AC _P1→ FC_AC _P1	$F^S_{FC\_EV} = 3$	A token with colour FC_AC: $v^{AT,TAS}_{FC\_AC} = v^{AT,TAS}_{cr,AC\_CH}$ $v_{h,FC\_AC} = 0$ $S^{FC\_AC}_f = cruise$ Variables used from other LPNs: • $v^{AT,TAS}_{cl,AC\_CH}$ from AC_CH
FC_AC_G5: FC_AC _P1→ FC_AC _P1	$F^S_{FC\_EV} = 4$	A token with colour FC_AC:

		$v_{FC\_AC}^{AT,TAS}=v_{de,AC\_CH}^{AT,TAS}$ $v_{h,FC\_AC}=v_{ROD,AC\_CH}^{h}$ $S_f^{FC\_AC}=descent$ Variables used from other LPNs: • v_{ROD,AC_CH}^{h}, $v_{de,AC\_CH}^{AT,TAS}$ from AC_CH
FC_AC_G6: FC_AC _P1→FC_AC _P1	$F_{FC\_EV}^{S}=7$	A token with colour FC_AC: $v_{FC\_AC}^{AT,TAS}=0$ $v_{h,FC\_AC}=0$ $S_f^{FC\_AC}=ground$
FC_AC_G7: FC_AC _P1→ FC_AC _P1	$F_{FC\_EV}^{S}=8$	A token with colour FC_AC: $S_f^{FC\_AC}=taxi$ $v_{FC\_AC}^{AT,TAS}=0$ $v_{h,FC\_AC}=0$
FC_AC_G8: FC_AC _P1→ FC_AC _P1	$F_{FC\_EV}^{S}=5$	A token with colour FC_AC: $v_{FC\_AC}^{AT,TAS}=v_{cl,AC\_CH}^{AT,TAS}$ $v_{h,FC\_AC}=v_{ROC,AC\_CH}^{h}$ $S_f^{FC\_AC}=$ climb Variables used from other LPNs: • v_{ROC,AC_CH}^{h}, $v_{cl,AC\_CH}^{AT,TAS}$ from AC_CH
FC_AC_G9: FC_AC _P1→ FC_AC _P1	$F_{FC\_EV}^{S}=6$	A token with colour FC_AC: $v_{FC\_AC}^{AT,TAS}=v_{cr,AC\_CH}^{AT,TAS}$ $v_{h,FC\_AC}=0$ $S_f=cruise$ Variables used from other LPNs: • $v_{cr,AC\_CH}^{AT,TAS}$ from AC_CH
FC_AC_G10: FC_AC _P1→ FC_AC _P1	$FRF_{critical}=true$	A token with colour FC_AC: $FRF_{critical}^{dec}=true$
FC_AC_G11: FC_AC _P1→FC_AC _P1	$FE_{critical}=true$	A token with colour FC_AC: $FE_{critical}^{dec}=true$ with probability P_{MAYDAY}^{dec}
FC_AC_G12: FC_AC _P1→ FC_AC _P1	$L_{div}=true$	A token with colour FC_AC: $I_{FC\_AC}^{ARR}=I_{FC\_SA}^{div}$

Parameters

Parameters	Description	Value	Explanation
P_{MAYDAY}^{dec}	Probability of declaring a mayday fuel, if the situation occurs	0.9999999	It is assumed that this situation occurs between 10^{-5} (fuel emergency frequency) and 10^{-9} (catastrophic accident). It can happen due to either a mistake or a violation. We assume a value in the middle of this spectrum, namely 10^{-7}. Then, $P_{MAYDAY}^{dec} = 1 - 10^{-7} = 0.9999999$

Incoming arcs within the same agent

There are arcs from FC_SA and FC_EV

- Flight variables are provided by FC_SA to several transitions.
- FC_EV informs FC_AC about the current phase of flight.

Outgoing arcs within the same agent

None.

Incoming arcs from other agents

There are incoming arcs from AC_CH and AD

- AC_CH provides speed-related variables.
- AD provides the planned route.

Outgoing arcs to other agents

There are arcs to FMS and ATCo_SA

- FMS inputs are realized after FC_AC variables are provided.
- ATCo_SA is updated from FC_AC.

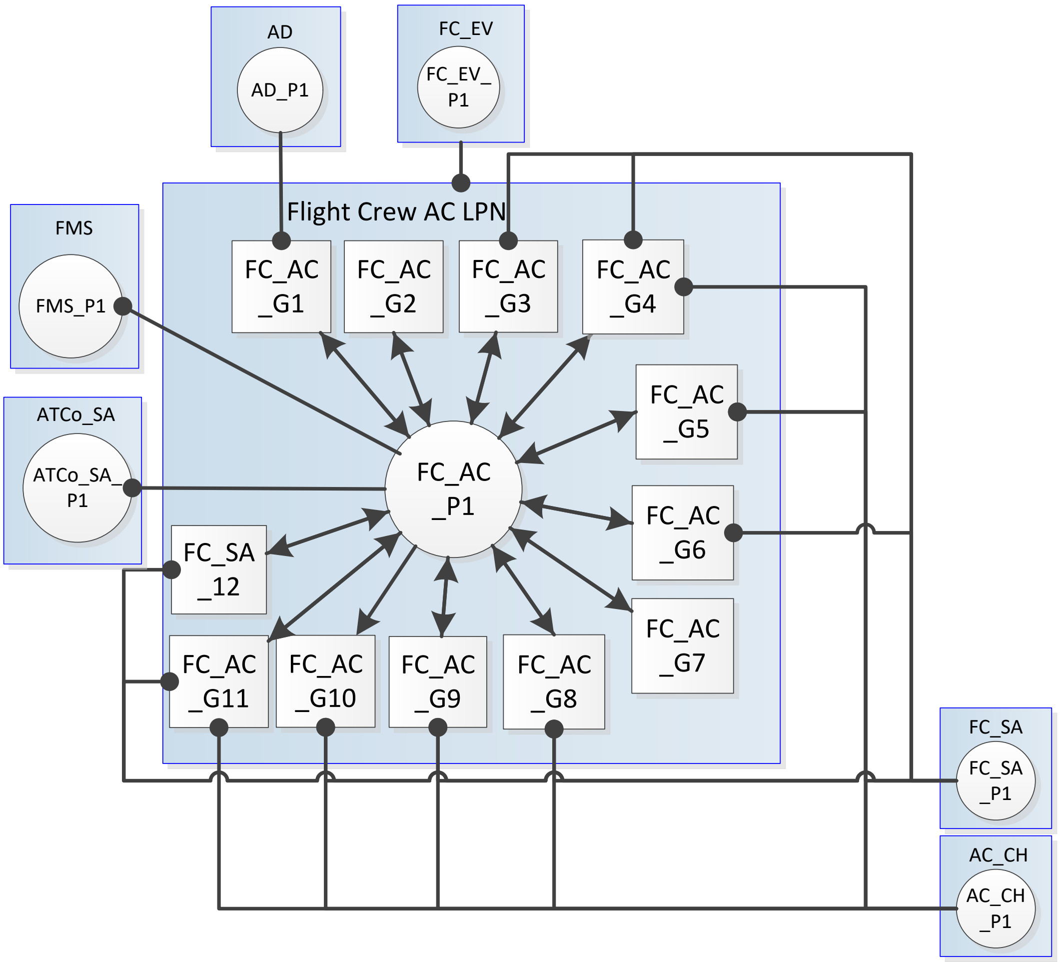

Figure 68 FC_AC interactions

D.8 Flight Management System (FMS)

Assumptions

1. FMS receives the current position and airspeed from Aircraft Agent (AC_ST).
2. Flight Crew uses the FMS to control the aircraft (set speed, altitude etc.).

Flight Management System

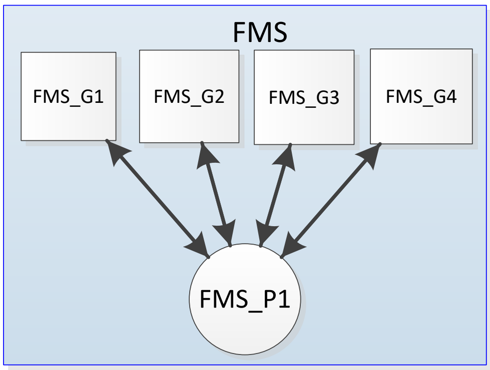

Figure 69 Flight Management System LPN

Colour type

FMS	**Notation**	**State Space**	**Description**
	x_{FMS}, y_{FMS}	$\mathbb{R}^2$	Aircraft's current position
	$x_{FMS}^{I_{alt}}, y_{FMS}^{I_{alt}}$	$\mathbb{Z}$	Position of the alternate airport
	$x_{FMS}^{I_{near}}, y_{FMS}^{I_{near}}$	$\mathbb{Z}$	Position of the nearest airport
	$x_{FMS}^{I_{near2}}, y_{FMS}^{I_{near2}}$	$\mathbb{Z}$	Position of the second nearest airport
	h_{FMS}	$\mathbb{R}_+$	Aircraft's current altitude
	v_h^{FMS}	$\mathbb{R}$	Rate of climb or descent
	v_{FMS}^{TAS}	$\mathbb{R}_+$	Aircraft's true airspeed (TAS)
	v_{FMS}^{GS}	$\mathbb{R}_+$	Aircraft's ground speed (GS)
	$s_{FMS} = \begin{pmatrix} s_{FMSx} \\ s_{FMSy} \end{pmatrix}$	$\mathbb{R}^2$	The direction of the aircraft
	J_{FMS}^{next}	$\mathbb{Z}$	Index of the next waypoint
	$x_{FMS}^{hold}, y_{FMS}^{hold}$	$\mathbb{R}^2$	The point that the holding procedure will start
	$d_{FMS}^{left,dest}$	$\mathbb{R}_+$	Distance to the destination from the current position
	$t_{FMS}^{left,dest}$	$\mathbb{R}_+$	Time to the destination from the current position
	d_{FMS}^i	$\mathbb{R}_+$	Distance to airport $i \in \{I_{alt}, I_{near}, I_{near2}\}$ from the current position
	$m_{f,FMS}^{dest}$	$\mathbb{R}_+$	Fuel upon landing at the destination airport
	$m_{f,FMS}^i$	$\mathbb{R}_+$	Fuel upon landing at the airport $i \in \{I_{alt}, I_{near}, I_{near2}\}$
	I_{dest}	$\mathbb{Z}$	Destination airport index
	I_i	$\mathbb{Z}$	Index of airport $i \in \{I_{alt}, I_{near}, I_{near2}\}$
	dm_f^{FMS}	$\mathbb{R}_+$	Fuel remaining

	$t_{W^{j=k}}$	$\mathbb{R}_+$	The time needed from the current position to the k_{th} waypoint, based on the current groundspeed
	L_{div}	$\{\text{true, false}\}$	Boolean variable denoting (true condition) that a diversion is executed.
	$L_{vectors}$	$\{\text{true, false}\}$	Boolean variable denoting (true condition) that ATCo radar vectors are received during the approach
	$W^j_{FMS} = \begin{pmatrix} W^j_x \\ W^j_y \end{pmatrix}$	$\mathbb{R}^2$	Waypoints that form the aircraft's route
	$W^j_{hold,FMS} = \begin{pmatrix} W^j_{x,hold} \\ W^j_{y,hold} \end{pmatrix}$	$\mathbb{R}^2$	Waypoints forming the holding pattern route
	N^{FMS}_W	$\mathbb{R}_+$	Total number of waypoints

Colour function

Place	**Colour type**	**Colour function**
FMS_P1	A token with colour FMS	$dt_{timerFMS} = -dt$

Initial marking

Place	Initial Colour
FMS_P1	A token with colour FMS $L_{div} = false$ $L_{vectors} = false$

Guard transitions

Transition	Guard Condition	Firing function
FMS_G1: FMS_P1→ FMS _P1	$F^S_{FC\_SA} = 0$	$W^j_{FMS} = \begin{pmatrix} W^j_{x,FC\_AC} \\ W^j_{y,FC\_AC} \end{pmatrix}$ $j = j_{next} = 1$ $x_{FMS} = x_A^{I^{AD}_{DEP}}$ $y_{FMS} = y_A^{I^{AD}_{DEP}}$ $h_{FMS} = 0$ Variables from other LPNs: • $W^j_{FC\_AC}$ from FC_AC • $x_A^{I^{AD}_{DEP}}, y_A^{I^{AD}_{DEP}}$ from AP
FMS_G2: FMS_P1→ FMS _P1	$t_{timerFMS} \leq 0$	A token with colour FMS $t_{timerFMS} = \Delta t_{timerFMS}$ $w^{n_2,m_2,t,h}_{FMS} = w^{n_2,m_2,t,h}_{EN}$

		$v_{FMS}^{AT,TAS} = v_{FC\_AC}^{AT,TAS}$ $v_{h,FMS} = v_{FC\_AC}^{h}$ $S_f^{FMS} = S_f^{FC\_AC}$ $I_{near} = \underset{i\in I-\{I_{alt},I_{dest}\}}{\arg\min} \left\lvert \begin{pmatrix} x_{FMS}-x_A^i \\ y_{FMS}-y_A^i \end{pmatrix} \right\rvert$ $I_{near2} = \underset{i\in -\{I_{alt},I_{dest},I_{near}\}}{\arg\min} \left\lvert \begin{pmatrix} x_{FMS}-x_A^i \\ y_{FMS}-y_A^i \end{pmatrix} \right\rvert$ $For\ all\ F_{AC\_EV}^{S}$ $v_x^{TAS} = s_{x,FMS} \cdot v_{FMS}^{AT,TAS}$ $v_y^{TAS} = s_{y,FMS} \cdot v_{FMS}^{AT,TAS}$ $v_{FMS}^{GS} = v_{FMS}^{AT,TAS} + \left\langle s_{FMS}, w_{FMS}^{n_2,m_2,t,h} \right\rangle$ $v_x^{GS} = s_{x,FMS} \cdot v_{FMS}^{AT,GS}$ $v_y^{GS} = s_{y,FMS} \cdot v_{FMS}^{AT,GS}$ $x_{FMS}^t, y_{FMS}^t = x_{FMS}^{t-1} + v_x^{GS}, y_{FMS}^{t-1} + v_y^{GS}$ $h_{FMS} = h_{FMS} + v_{h,FMS}$ $d_{FMS}^{left,dest} = \left\lvert W_{FMS}^{J_{next}} - \begin{pmatrix} x_{FMS} \\ y_{FMS} \end{pmatrix} \right\rvert d_{\sec}^{S_1} + \sum_{j=J_{next}}^{N_W-2} \left\lvert W_{FMS}^{j+1} - W_{FMS}^{j} \right\rvert d_{\sec}^{S_1}$ $t_{FMS}^{left,dest} = \frac{\left\lvert W_{FMS}^{J_{next}} - \begin{pmatrix} x_{FMS} \\ y_{FMS} \end{pmatrix} \right\rvert}{v_{FMS}^{GS}} + \frac{\sum_{j=J_{next}}^{N_W-2} \left\lvert W_{FMS}^{j+1} - W_{FMS}^{j} \right\rvert}{v_{FMS}^{GS}}$ $d_{FMS}^{i} = \left\lvert (x_{FMS}, y_{FMS}) - \begin{pmatrix} x_A^i \\ x_A^i \end{pmatrix} \right\rvert d_{\sec}^{S_1}, i \in \{I_{alt}, I_{near}, I_{near2}\}$ $dm_f^{FMS} = dm_f$ $m_{f,FMS}^{dest} = dm_f - \frac{d_{left,FMS}^{dest}}{v_{FMS}^{GS}} f_f^{AT,cruise}$ $m_{f,FMS}^{t} = dm_f - \frac{d_{FMS}^{i}}{V_{FMS}^{GS}} f_f^{AT,cruise}, i \in \{I_{alt}, I_{near}, I_{near2}\}$ $s_{FMS} = \begin{pmatrix} W_{x,FMS}^{j} - x_{FMS} \\ W_{y,FMS}^{j} - y_{FMS} \end{pmatrix}$ $j = J_{FMS}^{next}$ $If\ F_{AC\_EV}^{S} = 5 \lor F_{AC\_EV}^{S} = 6 : W_{hold,FMS}^{j} = \begin{pmatrix} W_{x,hold}^{j} \\ W_{y,hold}^{j} \end{pmatrix}$ $If\ F_{AC\_EV}^{S} = 4 :$ $If\ L_{vectors} = true : W_{FMS}^{J_{next}} = x_A^{I_{dest}}, y_A^{I_{dest}}$ Variables from other LPNs:

		• $W^{j}_{FC\_AC}$, v^{h}_{ROC,FC_AC}, $S_f^{FC\_AC}$ from FC_AC • $x_A^{I_{DEP}^{AD}}$, $y_A^{I_{DEP}^{AD}}$, $n_A^{I_{DEP}^{AD}}$, $m_A^{I_{DEP}^{AD}}$ from AP • $w_{EN}^{n_2,m_2,t,h}$ from EN • $f_f^{AT,cruise}$, dm_f from AC_FS • $L_{vectors}$ from FC_SA
FMS_G3: FMS_P1→ FMS _P1	$W^{j_{next}}_{x,FMS} - x_{FMS} \leq 0.1$ $W^{j_{next}}_{y,FMS} - y_{FMS} \leq 0.1$	A token with colour FMS: $J^{next}_{FMS} = J^{next}_{FMS} + 1$ Variables used from other LPNs: • $d^{S_2}_{sec}$ from EN
FMS_G4: FMS_P1→ FMS _P1	$L_{div} = true$	$I_{arr} = I_{div}$ $W^{j}_{FMS} = \begin{pmatrix} W^{j}_{x,div} \\ W^{j}_{y,div} \end{pmatrix}$ $j_{next} = 1$ Variables used from other LPNs: • I_{div} from FC_SA

Parameters

Parameters	**Description**	**Value**	**Parameters**
$\Delta t_{timerFMS}$	timer for updating FMS data	60 s	Minimum selectable time

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

None.

Incoming arcs from other agents

There are incoming arcs from AC_FS, FC_AC, EN, AP, AC_ST

- FMS receives fuel-related information from AC_FS.
- Flight Crew make inputs to the FMS, changing the values of it' variables.
- FMS receives airport related information from AP
- FMS receives the (real) wind characteristics from EN
- FMS receives the aircraft position and airspeed from AC_ST

Outgoing arcs to other agents

There are outgoing arcs to FC_SA and FC_FS

- Aircraft Fuel system receives flight parameters from the FMS.
- Flight Crew SA gets updated about flight variables through the FMS.

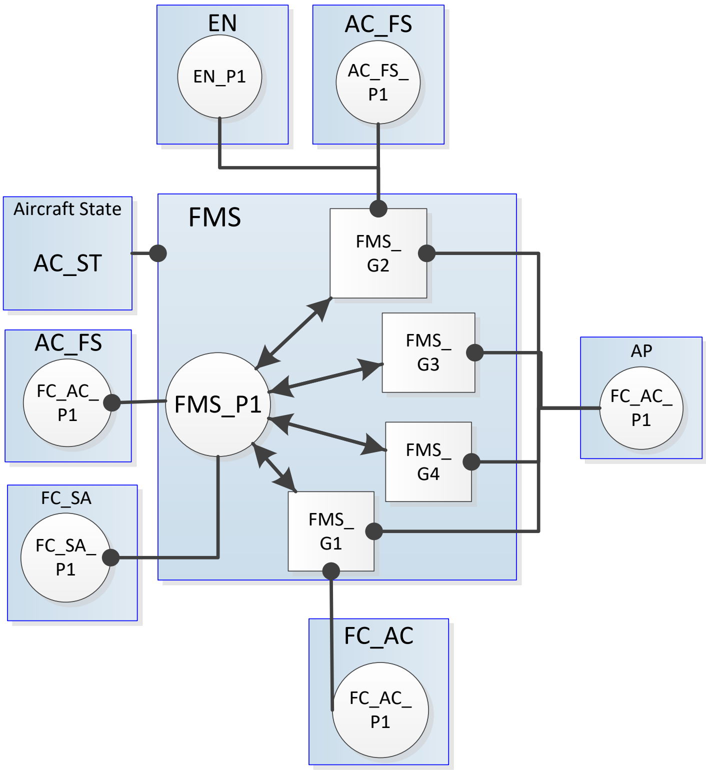

Figure 70 FMS interactions

D.9 Air Traffic Controller (ATCo)

Assumptions

1. There is only one type of ATCo , controlling the entire flight and all flight phases.
2. The identified hazards related to Air Traffic Controllers are grouped into two groups, as shown in Table 71. These hazards are modelled as separate LPNs.

Table 71 ATCo hazards

Hazards group number	Hazards group name	Hazards' serial numbers
HG1	Low-Efficiency radar vectors	H105,H114,H115
HG2	ATCo not in his/her position	H106,H107

ATCo Situation Awareness (ATCo SA)

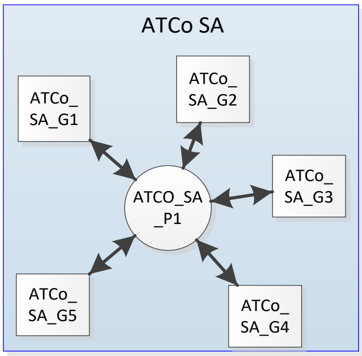

Figure 71 ATCo SA LPN

Colour type

Colour type	Notation	State Space	Description
ATCo	**1.FP ROUTE**		
	N_W^{ATCo}	$\mathbb{Z}$	number of waypoints
	$W_{ATCo\_SA}^{j}=\begin{pmatrix} W_{x,ATCo\_SA}^{j} \\ W_{y,ATCo\_SA}^{j} \end{pmatrix}$	$\mathbb{R}^2$	Flight plan route
	$I_{ATCo\_SA}^{DEP}$	$\mathbb{Z}$	index of the departure airport
	$I_{ATCo\_SA}^{ARR}$	$\mathbb{Z}$	index of the destination airport
	2.NOTAMS		
	$A_{NOTAM,ATCo\_SA}^{n_1,m_1,t}$	$\{true,\ false\}$	NOTAM containing information of the airspace availability
	3.WX (AP)		
	$M_{AP,ATCo\_SA}^{i,t}$	$\{0,1,2,3,4,5\}$	Meteorological forecast about airports weather
	4.Aircraft's current position		
	x_{ATCo_SA}, y_{ATCo_SA}	$\mathbb{R}, \mathbb{R}$	Coordinates of the current position of the aircraft, as perceived by the ATCo
	h_{ATCo_SA}	$\mathbb{R}_+$	The altitude of the current position of the aircraft, as perceived by the ATCo
	$s_{ATCo\_SA}=\begin{pmatrix} s_{x,ATCo\_SA} \\ s_{y,ATCo\_SA} \end{pmatrix}$	$\mathbb{R}^2$	The direction of the aircraft as perceived by the ATCo
	$n_2^{ATCo\_SA}, m_2^{ATCo\_SA}$	$\mathbb{Z}^2$	Coordinates of the current sector of the aircraft, as perceived by the ATCo
	$J_{next}^{ATCo\_SA}$	$\mathbb{Z}^2$	Index of next waypoint
	$S_{ATCo\_SA}^{m_2,next}, S_{ATCo\_SA}^{n_2,next}$	$\mathbb{Z}^2$	Indices of next sector
	4. EMERGENCY MANAGEMENT		
	$L_{ATCO\_SA}^{emergency}$	$\{true,\ false\}$	Flight Crew declaration of fuel emergency.

			When an emergency of other traffic is already declared ($L^{other}_{emergency} = true$), approach delays of Airport Hazards Group 1 and 2 will be shortened by E_{f1} and E_{f2} respectively. When no emergency is already declared, the two groups' approach delays will be shortened by E_{f3} and E_{f4}. We assume that delays of groups 3-4 cannot be reduced.
	$L^{other}_{emergency}$	$\{true, false\}$	Variable describing if other traffic has declared an emergency.
	7.TIME/DISTANCE AWARENESS		
	$t^{S_2,left}_{ATCO\_SA}$	$\mathbb{R}_+$	Time left in ATCO's sector
	$d^{S_2,left}_{ATCO\_SA}$	$\mathbb{R}_+$	Distance left in ATCO's sector
	8.Timers		
	$t^{ATCO\_AC,hz1}_{I_{ARR}}$	$\mathbb{R}_+$	Delay timer for airport operational delays (AP_HZ_G1)
	$t^{ATCO\_AC,hz2}_{I_{ARR}}$	$\mathbb{R}_+$	Delay timer for airport operational delays (AP_HZ_G2)
	$t^{ATCO\_AC,hz3}_{I_{ARR}}$	$\mathbb{R}_+$	Delay timer for airport operational delays (AP_HZ_G3)
	$t^{ATCO\_AC,hz4}_{I_{ARR}}$	$\mathbb{R}_+$	Delay timer for airport operational delays (AP_HZ_G4)
	$t^{ATCO\_AC,hz5}_{I_{DEP}}$	$\mathbb{R}_+$	Delay timer for airport operational delays (AP_HZ_G5)
	$t^{ATCO\_AC,hz6}_{I_{DEP}}$	$\mathbb{R}_+$	Delay timer for airport operational delays (AP_HZ_G6)
	$t^{taxi}_{ATCo\_AC}$	$\mathbb{R}_+$	Delay timer for taxi clearance provision
	$t^{take-off}_{ATCo\_AC}$	$\mathbb{R}_+$	Delay timer for take-off clearance provision
	$t^{land}_{ATCo\_AC}$	$\mathbb{R}_+$	Delay timer for landing clearance provision

Colour function

Place	**Colour type**	**Colour function**
ATCO_SA_P1	ATCO_SA	$dt^{ATCo\_SA}_{timer} = -dt$ $dt^{wx,del}_{ATCo\_SA} = -dt$ $dt^{ATCO\_AC,hz1}_{I_{ARR}} = -dt$ $dt^{ATCO\_AC,hz2}_{I_{ARR}} = -dt$ $dt^{ATCO\_AC,hz3}_{I_{ARR}} = -dt$

		$dt_{I_{ARR}}^{ATCO\_AC,hz4} = -dt$ $dt_{I_{DEP}}^{ATCO\_AC,hz5} = -dt$ $dt_{I_{DEP}}^{ATCO\_AC,hz6} = -dt$

Initial marking

Place	Initial Colour
ATCO_SA_P1	ATCo_SA $L_{ATCO\_SA}^{emergency} = false$ $L_{emergency}^{other} = true$, with probability $\mathrm{P}_{emergency}^{other}$ $L_{emergency}^{other} = false$, with probability $1\text{-}\mathrm{P}_{emergency}^{other}$

Guard transitions

Transition	Guard condition	Firing function
ATCO_SA _G1: ATCO_SA_P1→ ATCO_SA_P1	$F_{FC\_SA}^{S} = 0$	A token with colour ATCo_SA: $W_{ATCo}^{j} = W_{AD}^{j}$ $I_{ATCo}^{DEP} = I^{DEP}$ $I_{ATCo}^{ARR} = I^{ARR}$ Variables from other LPNs: • W_{AD}^{j}, I^{DEP}, I^{ARR} from AD
ATCO_SA _G2: ATCO_SA_P1→ ATCO_SA_P1	$t_{timer}^{ATCo\_SA} \leq 0 \wedge F_{FC\_SA}^{S} > 1$	A token with colour ATCo_SA: $t_{timer}^{ATCo\_SA} = \Delta t_{timer}^{ATCo\_SA}$ $x_{ATCo\_SA} = x_{ATCo\_SYS}$ $y_{ATCo\_SA} = y_{ATCo\_SYS}$ $h_{ATCo\_SA} = h_{ATCo\_SYS}$ $j_{ATCo\_SA}^{next} = j_{FC\_SA}^{next}$ $L_{emergency} = FE_{critical}^{dec}$ $If\ \ L_{ATCO\_SA}^{emergency} = true:$ $If\ \ \mathrm{L}_{emergency}^{other} = true: t_{I_{ARR}}^{hz1} = t_{I_{ARR}}^{hz1} \cdot E_{f1}, t_{I_{ARR}}^{hz4} = t_{I_{ARR}}^{hz4} \cdot E_{f2}$ $If\ \ \mathrm{L}_{emergency}^{other} = false: t_{I_{ARR}}^{hz1} = t_{I_{ARR}}^{hz1} \cdot E_{f3}, t_{I_{ARR}}^{hz4} = t_{I_{ARR}}^{hz4} \cdot E_{f4}$ Variables from other LPNs: • $x_{ATCo\_SYS}, y_{ATCo\_SYS}, h_{ATCo\_SYS}$ from ATC_SYS • $j_{FC\_SA}^{next}$ from FC_SA • $FE_{critical}^{dec}$ from FC_AC
ATCO_SA _G3: ATCO_SA_P1→	$dt_{ATCo\_SA}^{wx,del} \leq 0$	$t_{timerATCo\_SA}^{wx,del} = \Delta t_{timerATCo\_SA}^{wx,del}$ $A_{1,NOTAM,ATCo}^{n_1,m_1,t} = A_{1,NOTAM}^{n_1,m_1,t}$

ATCO_SA_P1		$A_{2,NOTAM,ATCo}^{n_2,m_2,t} = A_{2,NOTAM}^{n_2,m_2,t}$ $A_{3,NOTAM,ATCo}^{n_3,m_3,t} = A_{3,NOTAM}^{n_3,m_3,t}$ $M_{AP,ATCo}^{i,t} = M_{AP,met}^{i,t}$ $t_{i,FC\_SA}^{hz1} = t_i^{AP,1}$ $t_{i,FC\_SA}^{hz2} = t_i^{AP,2}$ $t_{i,FC\_SA}^{hz3} = t_i^{AP,3}$ $t_{i,FC\_SA}^{hz4} = t_i^{AP,4}$ $t_{i,FC\_SA}^{hz5} = t_i^{AP,5}$ $t_{i,FC\_SA}^{hz6} = t_i^{AP,6}$ $if\ A_{1,NOTAM,ATCo}^{W_{x,ATCo}^{j_{next}},W_{y,ATCo}^{j_{next}},t_{now}} = false:$ $W_{x,ATCo}^{j_{next}} = W_{x,ATCo}^{j_{next}} + d_1$ $W_{y,ATCo}^{j_{next}} = W_{y,ATCo}^{j_{next}}$ $if\ A_{2,NOTAM,ATCo}^{W_{x,ATCo}^{j_{next}},W_{y,ATCo}^{j_{next}},t_{now}} = false:$ $W_{x,ATCo}^{j_{next}} = W_{x,ATCo}^{j_{next}} + d_2$ $W_{y,ATCo}^{j_{next}} = W_{y,ATCo}^{j_{next}}$ $if\ A_{3,NOTAM,ATCo}^{W_{x,ATCo}^{j_{next}},W_{y,ATCo}^{j_{next}},t_{now}} = false:$ $W_{x,ATCo}^{j_{next}} = W_{x,ATCo}^{j_{next}} + d_3$ $W_{y,ATCo}^{j_{next}} = W_{y,ATCo}^{j_{next}}$ Variables from other LPNs: • $A_1^{n_1,m_1,t}$ from EN • $A_{2,NOTAM}^{n_1,m_1,t}$ $A_{3,NOTAM}^{n_1,m_1,t}$ from NOTAM • $M_{AP,met}^{i,t}$ from MET • $t_i^{AP,1},t_i^{AP,3},t_i^{AP,3},t_i^{AP,4},t_i^{AP,5},t_i^{AP,6}$ from AP

Parameters

Parameters	Description	Value	Explanation
$\Delta t_{timer}^{ATCo\_SA}$	Timer for guard transition G2	60 s	Minimum selectable time
$\Delta t_{timerATCo\_SA}^{wx,del}$	Timer for guard transition G3	60 s	Minimum selectable time
P_{emerg}	Probability of another aircraft emergency	10^{-15}	Based on [1][2][3], it is assumed that the probability of an emergency declaration for a single airport is $4 \cdot 10^{-7}$. We assume then that the probability for two simultaneous emergencies in the same airport is $(4 \cdot 10^{-7})^2 \cong 10^{-15}$.

E_{f1}	The factor for expediting approach (delays reduction) when another emergency is in progress (for AP_HZ_G1)	0.3	Model parameter
E_{f2}	The factor for expediting approach when another emergency is in progress (for AP_HZ_G2)	0.3	Model parameter
E_{f3}	The factor for expediting approach when no other emergency is in progress	0.5	Model parameter
E_{f4}	The factor for expediting approach when no other emergency is in progress	0.5	Model parameter
d_1	Deviation (provided by ATC vectors) when S_1 sector is unavailable (due to weather)	20000m	[4] Typical thunderstorm diameter
d_2	Deviation (provided by ATC vectors) when S_2 sector is unavailable (due to weather)	100000m	Assumption of an average area size which will become unavailable, upon triggering of EN_HZ_G2
d_3	Deviation (provided by ATC vectors) when S_3 sector is unavailable (due to weather)	160000m	Assumption of an average area size which will become unavailable, upon triggering of EN_HZ_G3

[1]http://aviation.globalincidentmap.com/

[2]https://www.bravotv.com/jetset/emergency-landing-by-type-us-2017-passenger-planes

[3]https://www.faa.gov/data_research/aviation_data_statistics/operational_metrics/

[4] National Severe Storms Laboratory (2006-10-15). "A Severe Weather Primer: Questions and Answers about Thunderstorms". National Oceanic and Atmospheric Administration.

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

None.

Incoming arcs from other agents

There are incoming arcs from NOTAM, MET, AD, AP:

- NOTAM agent provides information about the current airspace situation.
- MET agent provides the current meteorological forecast.
- AD provides the initial flight plan.
- AP provides airport related variables.

Outgoing arcs to other agents

None.

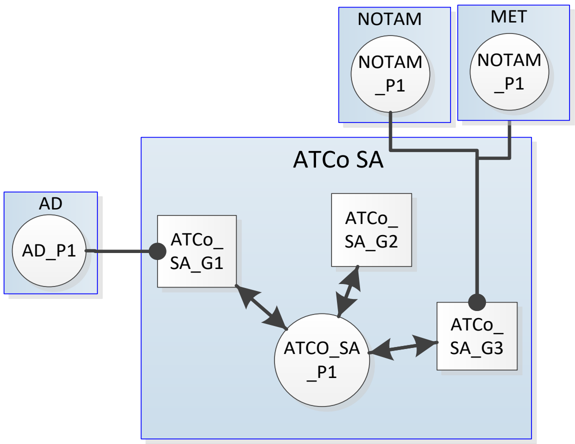

Figure 72 ATCo_SA interactions

ATCo Actions

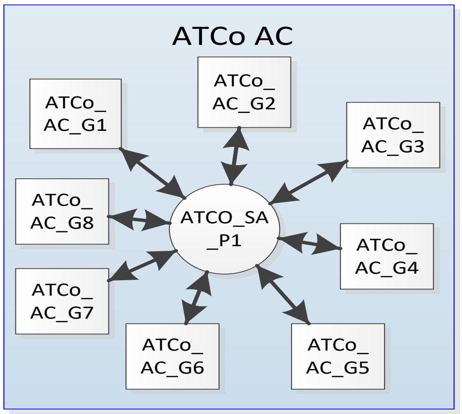

Figure 73 ATCo_AC LPN

Colour type

Colour type	**Notation**	**State Space**	**Description**
ATCo_AC	**ATCo Clearances**		
	$C^{startup}_{ATCo\_AC}$	$\{true, false\}$	ATCo clearance for start-up (After operational delays have finished)
	$C^{taxi}_{ATCo\_AC}$	$\{true, false\}$	ATCo clearance for taxi-out
	$C^{take-off}_{ATCo\_AC}$	$\{true, false\}$	ATCo clearance for take-off
	$C^{land}_{ATCo\_AC}$	$\{true, false\}$	ATCo clearance for landing
	$C^{dep1}_{ATCo\_AC}$	$\{true, false\}$	ATCo imposed delay during taxing due to operational reasons.
	$C^{dep2}_{ATCo\_AC}$	$\{true, false\}$	Delays during taxing due to weather.
	$C^{app1}_{ATCo\_AC}$	$\{true, false\}$	ATCo clearance for approach (After operational delays have finished)
	$C^{app2}_{ATCo\_AC}$	$\{true, false\}$	ATCo clearance for approach (After severe

			weather phenomena over airport have finished)
	ATCo operational variables		
	$W^j_{ATCo\_AC} = \begin{pmatrix} W^j_{x,ATCo\_AC} \\ W^j_{y,ATCo\_AC} \end{pmatrix}$	$\mathbb{R},\mathbb{R}$	ATCo radar vectors
	$R^{change}_{ATCo\_AC}$	$\{true,\ false\}$	Runway change at the airport of arrival

Colour function

Place	**Colour type**	**Colour function**
ATCo_AC_P1	ATCo_AC	$dt^{taxi}_{ATCo\_AC} = -dt$ $dt^{take-off}_{ATCo\_AC} = -dt$ $dt^{land}_{ATCo\_AC} = -dt$

Initial marking

Place	Initial Colour
ATCo_AC_P1	A token with colour ATCo_AC $R^{change}_{ATCo} = true,\ with\ probability\ P_{rwy}$ $R^{change}_{ATCo} = false,\ with\ probability\ 1\text{-}P_{rwy}$ $t^{taxi,cl}_{FC\_SA} \sim N(\mu_{TXC},\sigma_{TXC},l_{TXC},u_{TXC})$ $t^{takeoff}_{ATCo} \sim N(\mu_{TC},\sigma_{TC},l_{TC},u_{TC})$ $t^{landing}_{ATCo} \sim N(\mu_{LC},\sigma_{LC},l_{LC},u_{LC})$ $C^{startup}_{ATCo\_AC} = false$ $C^{Taxi}_{ATCo} = false$ $C^{take-off}_{ATCo} = false$ $C^{landing}_{ATCo} = false$ $C^{app}_{ATCo\_AC} = false$ $C^{app2}_{ATCo\_AC} = false$ $C^{dep}_{ATCo\_AC} = false$ $C^{dep2}_{ATCo\_AC} = false$

Guard transitions

Transition	Guard condition	Firing function
ATCO_AC _G1: ATCO_AC_P1→ ATCO_AC_P1	$F^S_{FC\_EV} = -1 \wedge t^{ATCO\_AC,hz6}_{I_{DEP}} \leq 0$	$C^{startup}_{ATCo\_AC} = true$ $C^{dep2}_{ATCo\_AC} = true$ Variables used from other LPNs: • t^{hz5}_i from AP_HG_5
ATCO_AC _G2: ATCO_AC_P1→	$F^S_{FC\_EV} = 0 \wedge t^{ATCO\_AC,hz5}_{I_{DEP}} \leq 0 \wedge$ $t^{taxi}_{ATCo\_AC} \leq 0$	$C^{Taxi}_{ATCo} = true$

ATCO_AC_P1		
ATCO_AC _G3: ATCO_AC_P1→ ATCO_AC_P1 FC_AC_P1	$F^{S}_{FC\_EV} = 1 \wedge t^{takeoff}_{ATCo} \leq 0 \wedge$ $t^{ATCO\_AC,hz5}_{I_{DEP}} \leq 0$	$C^{take-off}_{ATCo\_AC} = true$ $C^{dep1}_{ATCo\_AC} = true$ $if\ Y_{ATC\_SYS} = true : W^{j_{next}}_{ATCo\_AC} = W^{j=5}_{AD}$ Variables used from other LPNs ● Y_{ATC_SYS}
ATCO_AC _G4: ATCO_AC_P1→ ATCO_AC_P1 FC_AC_P1	$F^{S}_{FC\_EV} = 4,5,6 \wedge t^{ATCO\_AC,hz1}_{I_{ARR}} \leq 0 \wedge$ $t^{ATCO\_AC,hz2}_{I_{ARR}} \leq 0 \wedge t^{ATCO\_AC,hz3}_{I_{ARR}} \leq 0 \wedge$ $t^{ATCO\_AC,hz4}_{I_{ARR}} \leq 0$	$C^{app1}_{ATCo\_AC} = true$ $if\ H^{2}_{ATCo} = true :\ t^{ATCO\_AC,hz4}_{I_{ARR}} = M_{s}$ Variables used from other LPNs ● H^{2}_{ATCo} from ATC_HZ1
ATCO_AC _G5: ATCO_AC_P1→ ATCO_AC_P1 FC_AC_P1	$W^{I_{ARR},t_{now}}_{AP\_WX} = 0 \wedge F^{S}_{FC\_EV} = 4,5,6$	$C^{app2}_{ATCo\_AC} = true$
ATCo_AC_G6: ATCo_AC_P1→ ATCo_AC_P1	$F^{S}_{FC\_EV} = 4 \wedge C^{app1}_{ATCo\_AC} = true \wedge$ $C^{app2}_{ATCo\_AC} = true \wedge Y_{surv} = true$	If $Y_{ATC\_SYS} = true$: $L_{vectors} = true$ Variables used from other LPNs • Y_{ATC_SYS} from ATCo_SA
ATCO_AC _G7: ATCO_AC_P1→ ATCO_AC_P1 FC_AC_P1	$F^{S}_{FC\_EV} = 4 \wedge C^{app1}_{ATCo\_AC} = true \wedge$ $C^{app2}_{ATCo\_AC} = true$	$C^{landing}_{ATCo} = true$
ATCO_AC _G8: ATCo_AC_P1→ ATCo_AC_P1	$F^{S}_{FC\_EV} = 4 \wedge C^{app1}_{ATCo\_AC} = true \wedge$ $C^{app2}_{ATCo\_AC} = true \wedge R^{change}_{ATCo} = true$	If $R^{change}_{ATCo\_AC} = true :$ $If\ H^{1}_{ATCo} = false :$ $W^{N_w-3}_{ATCo\_AC} = \begin{pmatrix} x^{I_{arr}} - 0.45 \\ y^{I_{arr}} \end{pmatrix} W^{N_w-1}_{ATCo\_AC} = \begin{pmatrix} x^{I_{arr}} + 0.7 \\ y^{I_{arr}} \end{pmatrix}$ $W^{N_w-2}_{ATCo\_AC} = \begin{pmatrix} x^{I_{arr}} - 0.45 \\ y^{I_{arr}} + 0.7 \end{pmatrix} W^{N_w}_{ATCo\_AC} = \begin{pmatrix} x^{I_{arr}} \\ y^{I_{arr}} \end{pmatrix}$ $if\ H^{1}_{ATCo} = false$ $W^{N_w-3}_{ATCo\_AC} = \begin{pmatrix} x^{I_{arr}} - 0.25 \\ y^{I_{arr}} \end{pmatrix} W^{N_w-1}_{ATCo\_AC} = \begin{pmatrix} x^{I_{arr}} + 0.5 \\ y^{I_{arr}} \end{pmatrix}$ $W^{N_w-2}_{ATCo\_AC} = \begin{pmatrix} x^{I_{arr}} - 0.25 \\ y^{I_{arr}} + 0.5 \end{pmatrix} W^{N_w}_{ATCo\_AC} = \begin{pmatrix} x^{I_{arr}} \\ y^{I_{arr}} \end{pmatrix}$

Parameters

Parameters	Description	Value	Explanation
P_{rwy}	Probability of runway change by ATCo	0.0001	We assume 1 unplanned runway change per 10.000 flights, or

			$P_{rwy} = 0.0001$
$\mu_{TXC},\sigma_{TXC},l_{TXC},u_{TXC}$	Truncated normal distribution parameters of the variable $t^{taxi,cl}_{FC\_SA}$	$0,60,0,300\ s$	Model parameter
$\mu_{TC},\sigma_{TC},l_{TC},u_{TC}$	Truncated normal distribution parameters of the variable $t^{takeoff}_{ATCo}$	$0,60,0,300\ s$	Model parameter
$\mu_{LC},\sigma_{LC},l_{LC},u_{LC}$	Truncated normal distribution parameters of the variable $t^{landing}_{ATCo}$	$0,60,0,300\ s$	Model parameter
M_s	A random very large number indicating that the airport delays are very long	$1000000000\ s$	A number which will immediately make the FC to divert.

Incoming arcs within the same agent

There are arcs from ATCo_SA

- ATCo_SA provides information to ATCo_AC

Outgoing arcs within the same agent

There are arcs to ATCo_SA

- ATCo_SA is updated by ATCo_AC.

Incoming arcs from other agents

There are incoming arcs from AD

- ATCo_AC receives information from AD.

Outgoing arcs to other agents

There are outgoing arcs to FC_SA

- ATCo_SA provides information to FC_SA

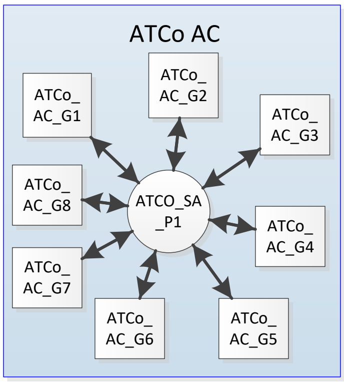

Figure 74 ATCo_AC with interactions

ATCo Hazards group 1 ATCO_HG1 LPN

Assumptions

- ATCO_HG1: Nominal condition, the hazard is not triggered.
- ATCO_HG1_T: Non-nominal condition, low-quality ATC is expected.

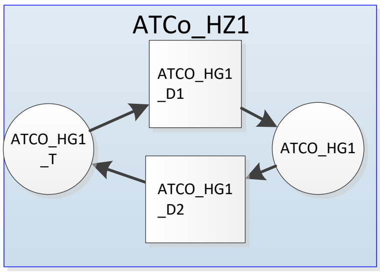

Figure 75 ATCo HZ1 LPN

Colour type

Colour type	Notation	State Space	Description
ATCO_HG1	H^1_{ATCo}	$\{true, false\}$	if $H^1_{ATCo} = true$, low-efficiency radar vectors by ATCo are expected (and thus, increased flight route)

Colour function

Place	Colour type	Colour function
All places	ATCO_HZ1	constant

Initial marking

Place	Initial Colour
ATCO_HG1	A token with colour ATCO_HZ1

Delay transitions

Transition	Delay rate	Firing function
ATCO_HG1_D1: ATCO_HG1_T→ ATCO_HG1	Delay ~ Exp($\Delta t_{ATCO\_HG1\_D1}$)	A token with colour ATCO_HZ1 $H^1_{ATCo} = false$
ATCO_HG1_D2: ATCO_HG1→ ATCO_HG1_T	Delay ~ Exp($\Delta t_{ATCO\_HG1\_D2}$)	A token with colour ATCO_HZ1 $H^1_{ATCo} = true$

Parameters

Parameters	Description	Value	Explanation
$p^{ATCO\_HG1}_{non}$	Probability that $H^1_{ATCo} = true$	$59994000s$	As radar vectors efficiency is difficult to be quantified, we assume that one ATCo shift per 10.000 shifts could have provided more efficient vectors, and as such $p^{ATCO\_HG1}_{non} = 10^{-4}$. $\Delta t_{ATCO\_HG1\_D1} = \mu^{HG1}_{ATCO} \frac{1 - p^{ATCO\_HG1}_{non}}{p^{ATCO\_HG1}_{non}} = 59994000s$ $\Delta t_{ATCO\_HG1\_D2} = \mu^{HG1}_{ATCO} = 6000s$
μ^{HG1}_{ATCO}	Mean duration of the hazards group 1 triggering	$6000s$	One shift mean duration is 100min on average [1]

[1] https://en.wikipedia.org › wiki › Air_traffic_controller

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

There is one arc to ATCo_AC

- ATCo_AC is updated when the hazard is triggered.

Incoming arcs from other agents

None.

Outgoing arcs to other agents

None.

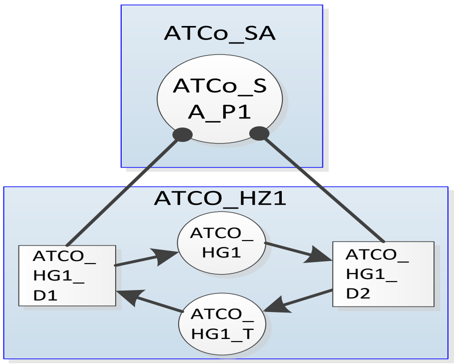

Figure 76 ATCo_HZ1 interactions

ATCo Hazards group 2 ATCO_HG2 LPN

Assumptions

- ATCO_HG2: Nominal condition, the hazard is not triggered.
- ATCO_HG2_T: Non-nominal condition, ATCo will be absent and as such, delays will occur.

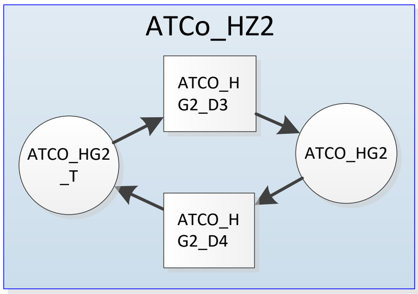

Figure 77 ATCo Hazards group 2

Colour type

Colour type	Notation	State Space	Description
ATCO_HG2	H^2_{ATCo}	$\{true, false\}$	If $H^2_{ATCo} = true$, ATCo will unexpectedly be absent from his/her position. This will lead to airport closure.

Colour function

Place	Colour type	Colour function
All places	ATCO_HZ2	constant

Initial marking

Place	Initial Colour
ATCO_HG2	A token with colour ATCO_HZ2 $H_{ATCo}^{2} = false$

Delay transitions

Transition	Delay rate	Firing function
ATCO_HG2_D3: ATCO_HG3_T→ATCO_HG3	Delay ~ Exp($\Delta t_{\text{ATCO\_HG2\_D3}}$)	A token with colour ATCO_HZ2 $H_{ATCo}^{2} = false$
ATCO_HG2_D4: ATCO_HG3→ATCO_HG3_T	Delay ~ Exp($\Delta t_{\text{ATCO\_HG2\_D4}}$)	A token with colour ATCO_HZ2 $H_{ATCo}^{2} = true$

Parameters

Parameters	Description	Value	Explanation
$p_{non}^{\text{ATCO\_HG2}}$	Probability that $H_{ATCo}^{1} = true$	$31560922s$	We assume this event to occur once per year for the entire environment. Thus: $p_{non}^{ATCO\_HG2} = 0.00057$ $\Delta t_{\text{ATCO\_HG2\_D3}} = \mu_{ATCO}^{HG2} \dfrac{1 - p_{non}^{\text{ATCO\_HG2}}}{p_{non}^{\text{ATCO\_HG2}}} = 31560922s$ $\Delta t_{\text{ATCO\_HG2\_D4}} = \mu_{ATCO}^{HG2} = 18000s$
μ_{ATCO}^{HG2}	Mean duration of the hazards group 1 triggering	$18000s$	Based on the same rationale used before for EN_GH_3, we assume a maximum of 5 hours of effective triggering. $\mu_{ATCO}^{HG2} = 18000s$

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

There are two arcs to ATC_SA and ATC_AC

Incoming arcs from other agents

None.

Outgoing arcs to other agents

None.

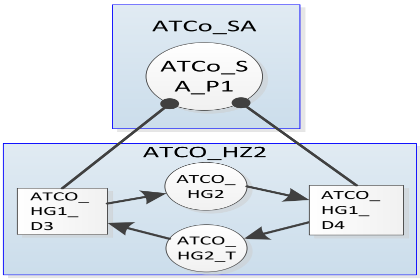

Figure 78 ATCo_HZ2 interactions

D.10 ATC system (ATCS)

ATC SYSTEM

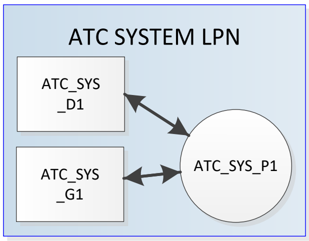

Figure 79 ATC Systems LPN

Colour type

Colour type	Notation	State Space	Description
ATC_SYS	Y_{ATC_SYS}	$\{true, false\}$	ATC systems related to surveillance condition (true for working, false for not working).

Colour function

Place	Colour type	Colour function
ATC_SYS	ATC_SYS	constant

Initial marking

Place	Initial Colour
ATC_SYS_P1	A token with colour ATC_SYS $Y_{ATC\_SYS} = true$ $t_{ATC\_SYS} = -dt_{ATC\_SYS}$

Delay transitions

Transition	Delay rate	Firing function
ATC_SYS_D1: ATC_SYS_P1→ ATC_SYS_P1	Delay ~ Exp($\Delta t_{ATC\_SYS\_D1}$)	A token with colour ATC_SYS $Y_{ATC\_SYS} = false$

Guard transitions

Transition	Delay rate	Firing function
ATC_SYS_G1: ATC_SYS_P1→ ATC_SYS_P1	$t_{ATC\_SYS} \leq 0$	A token with colour ATC_SYS $x_{ATC\_SYS} = x_{FMS}$ $y_{ATC\_SYS} = y_{FMS}$ $h_{ATC\_SYS} = h_{FMS}$ $t_{ATC\_SYS} = t_{ATC\_SYS}^{timer}$

Parameters

Parameters	**Description**	**Value**	**Explanation**
$p_{non}^{ATCO\_SYS}$	Probability that $p_{non}^{ATCO\_SYS} = true$	0.000057	We assume that the ATC system may collapse less than once per 10 years for a single airport. As such: $p_{non}^{ATCO\_SYS} = 0.000025$ $\Delta t_{\mathrm{ATC\_SYS\_D1}} = \mu_{ATCO\_SYS} \dfrac{1 - p_{non}^{ATCO\_SYS}}{p_{non}^{ATCO\_SYS}} = 3167920800s$
μ_{ATCO_SYS}	Mean duration of the failure duration	79200s	We assume that the mean duration of the triggering will be the entire time of the simulation of the specific flight, which is at max 22h. As such, $\mu_{ATCO\_SYS} = 79200s$. As long as the hazard's duration is the entire duration of the simulation of a specific flight, there is no need for a second delay function for triggering the nominal condition.

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

None.

Incoming arcs from other agents

None.

Outgoing arcs to other agents

There is one outgoing arc to ATCo_SA:

- ATCo SA is updated about the current situation of the ATC systems.

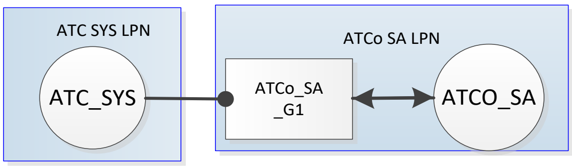

Figure 80 ATC Systems LPN interactions

D.11 Cabin Crew (CC)

Assumptions

1. An aircraft may take off or land, only upon confirmation of the cabin crew that the cabin is secure.
2. In case of fuel emergency, cabin security is not considered.

Cabin Crew LPN

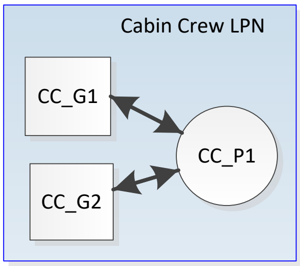

Figure 81 Cabin Crew LPN

Colour type

Colour type	Notation	State Space	Description
CC	$C_{\sec,CC}^{to}$	$\{true, false\}$	Cabin security condition before take-off. After any possible delay, the cabin condition may become true and the aircraft may take off.
	$C_{\sec,CC}^{land}$	$\{true, false\}$	Cabin security before landing. If true, the aircraft may continue approach for landing. If false, the aircraft must execute a go-around procedure.
	$t_{to,CC}^{delay}$	$\mathbb{R}_+$	Timer for cabin security delay before take-off
	$t_{land,CC}^{delay}$	$\mathbb{R}_+$	Timer for cabin security delay before landing

Colour function

Place	Colour type	Colour function
CC_P1	CC	$dt_{to,CC}^{delay} = -dt$ $dt_{land,CC}^{delay} = -dt$

Initial marking

Place	Initial Colour
CC_P1	A token with colour CC: $t_{to,CC}^{delay} = 0$, with probability $1\text{-}P_{cabin}^{takeoff}$ $t_{to,CC}^{delay} \sim N(\mu_{CC}^{to}, \sigma_{CC}^{to}, l_{CC}^{to}, u_{CC}^{to})$, with probability $P_{cabin}^{takeoff}$

	$t^{delay}_{land,CC} = 0$, with probability 1-P^{land}_{cabin} $t^{delay}_{land,CC} \sim N(\mu^{land}, \sigma^{land}, l^{land}, u^{land})$, with probability P^{land}_{cabin}

Guard transitions

Transition	Guard condition	Firing function
CC_G1: CC _P1→ CC _P1	$t^{delay}_{to,CC} \le 0 \wedge F^{S}_{AC\_EV} = 1$	A token with colour CC $C^{to}_{sec,CC} = true$
CC_G2: CC _P1→ CC _P1	$t^{delay}_{land,CC} \le 0 \wedge F^{S}_{AC\_EV} = 7$	A token with colour CC $C^{land}_{sec,CC} = true$

Parameters

Parameters	**Description**	**Value**	**Explanation**
$P^{takeoff}_{cabin}$	Probability of incurring cabin security delay before take-off	0.00028	According to IATA, there was 1 incident of unruly passenger per 1053 flights in 2017. Assuming that 70% of them concern after take-off incidents and 30% pre-take-off incidents, we may conclude that the probability of pre-take-off delay due to cabin incidents lies in the area of 0.3 every 1053 flights.
P^{land}_{cabin}	Probability of incurring cabin security delay before landing	0.00066	Following the above explanation, we calculate a probability of 0.7 every 1053 flights
$\mu^{to}_{CC}, \sigma^{to}_{CC}, l^{to}_{CC}, u^{to}_{CC}$	Truncated normal distribution parameters of the delay time incurred by non-secure cabin before departure	$120, 60, 0, 480s$	Assumption of time needed for cabin issue resolution before take-off
$\mu^{land}, \sigma^{land}, l^{land}, u^{land}$	Mean, standard deviation, min and max time parameters of the delay time distribution incurred by non-secure cabin, before landing	$360, 120, 240, 1200s$	Assumption of time needed for cabin issue resolution before landing

[1] https://www.iata.org/policy/consumer-pax-rights/Documents/unruly_pax_infographic_2017.pdf

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

None.

Incoming arcs from other agents

None.

Outgoing arcs to other agents

There are two outgoing arcs to FC_SA:

- FC_SA receives confirmation about the cabin security, before take-off and before landing.

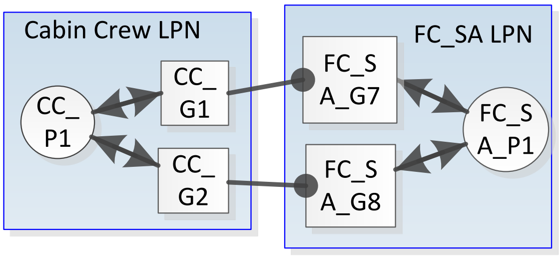

Figure 82 CC agent interactions

D.12 Maintenance Repair and Overhaul (MRO)

MRO LPN

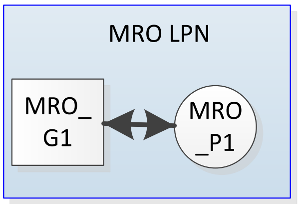

Figure 83 Maintenance, Repair, Overhaul LPN

Colour type

Colour type	Notation	State Space	Description
MRO	$f^{ENG}_{factor,MRO}$	$\mathbb{R}_+$	Increased consumption factor due to MEL/CDL or degraded engines provided to the flight crew by MRO. If aircraft flies under the aforementioned circumstances, this factor will be provided to crew with probability P^1_{MRO}.

Colour function

Place	Colour type	Colour function
MRO_P1	MRO	constant

Initial marking

Place	Initial Colour

MRO_P1	A token with colour MRO

Guard transitions

Transition	Guard condition	Firing function
MRO_G1: MRO _P1→ MRO _P1	$F^{S}_{AC\_EV} = -1$	A token with colour MRO: $f^{ENG}_{factor,MRO} = f^{ENG}_{factor}$, with probability P^{1}_{MRO} $f^{ENG}_{factor,MRO} = f^{ENG}_{nom}$, with probability 1-$P^{1}_{MRO}$ Used variables from other LPNs: • f^{ENG}_{factor} from AC_HZ

Parameters

Parameters	**Description**	**Value**	**Explanation**
P^{1}_{MRO}	Probability of increased fuel consumption notice by MRO to FC	0.9999	We assume that the probability of the event ”MRO does not provide the correct non-nominal consumption information to FC” to be once over 10000 flights, or $P^{1}_{MRO} = 1 - \frac{1}{10000} = 0.9999$
f^{ENG}_{nom}	Normal consumption condition factor	1	

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

None.

Incoming arcs from other agents

There are two incoming arcs from FC_EV and AC_HZ

- MRO receives the information that the pre-flight phase is active.
- MRO receives the f^{ENG}_{factor} from AC_HZ

Outgoing arcs to other agents

There is one outgoing arc to FC_PL:

- FC_PL receives the engines ‘consumption factor.

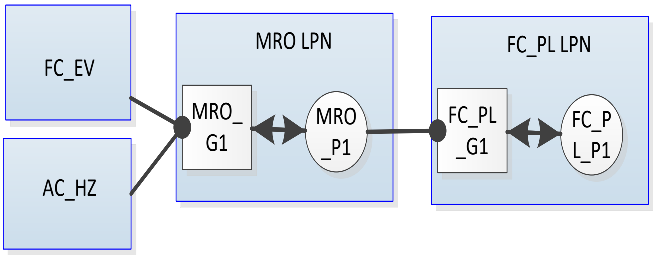

Figure 84 MRO LPN interactions

D.13 Ground handling (GH)

Ground Handling LPN

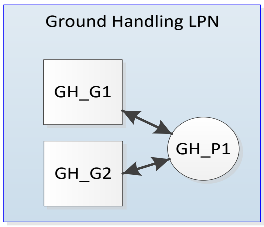

Figure 85 GH LPN

Colour type

Colour Type	Notation	State Space	Description
GH	H_{GH}^{hadl}	$\{true,\ false\}$	Handling service completed
	$m_{f,GH}^{actual,up}$	$\mathbb{R}_+$	Actual fuel quantity uplifted
	t_{GH}	$\mathbb{R}_+$	Delay time introduced by ground handlers

Colour function

Place	Colour type	Colour function
GH_P1	GH	$dt_{GH} = -dt$

Initial marking

Place	Initial Colour
GH_P1	A token with colour GH: $H_{GH}^{hadl} = false$ $t_{GH} \sim N(\mu_{GH}, \sigma_{GH}, l_{GH}, u_{GH})$

Guard transitions

Transition	Guard conditions	Firing function
GH_G1: GH _P1→GH _P1	$F_{AC\_EV}^{S} = -1$	A token with colour GH: $m_{f,GH}^{actual,uplift} = m_{f,GH}^{asked,uplift}$ with probability $P_{f,asked}$ $m_{f,GH}^{actual,uplift} \sim N_{f,asked}^{error}(\mu_{GH}^{AU}, \sigma_{GH}^{AU}, l_{GH}^{AU}, u_{GH}^{AU})$, with probability $1-P_{f,asked}$ Used variables from other LPNs: • $m_{f,uplift}^{asked}$ from FC_PL
GH_G2: GH _P1→GH _P1	$t_{GH} \leq 0 \wedge F_{AC\_EV}^{S} = 0$	A token with colour GH: $H_{GH}^{hadl} = true, after\ t_{GH} \sim N(\mu_{GH}, \sigma_{GH}, l_{GH}, u_{GH}) \leq 0$

Parameters

Parameters	Description	Value	Explanation

$\mu_{GH}^{AU}, \sigma_{GH}^{AU},$ l_{GH}^{AU}, u_{GH}^{AU}	Truncated normal distribution parameters of error for fuel uplift	$m_{f,GH}^{asked,uplift}, 500,$ $m_{f,GH}^{asked,uplift} - 3000, \quad \text{kg}$ $m_{f,GH}^{asked,uplift} + 3000$	Assumption of fuel uplift mistake values
$P_{f,asked}$	Probability of uplifting the aircraft with the asked amount	0.999999	We assume that the probability of the event ”GH does not fuel up the requested amount of fuel and FC does not detect it before take-off” to be once over 1000000 flights, or $P_{f,asked} = 1 - \frac{1}{1000000} = 0.999999$
$\mu_{GH}, \sigma_{GH},$ l_{GH}, u_{GH}	Truncated normal distribution parameters of time delay incurred by GH to start the pushback	$60, 60, 0, 900\ s$	Assumption of incurred delays by GH

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

None.

Incoming arcs from other agents

There is one incoming arc to GH LPN

- Ground handlers receive information that the pre-flight phase is active.

Outgoing arcs to other agents

There are outgoing arcs to Flight Crew SA and Aircraft Evolution

- Flight Crew SA receives information about whether or not the aircraft’s handling is finished.
- Aircraft can start up (P0) only after GH service is finished.

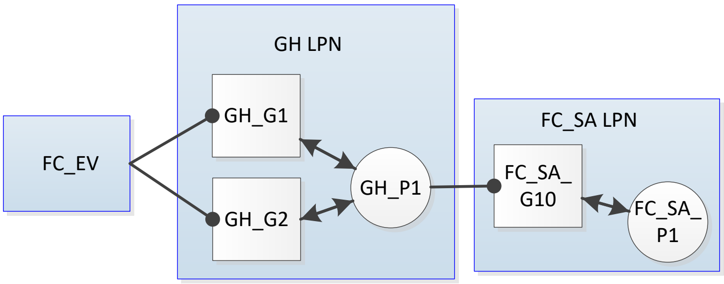

Figure 86 GH LPN interactions

D.14 Meteorological Service (MET)

Assumptions

1. Met service updates its weather information every 30 minutes.
2. Met service can provide forecasts only with an error, which is ascending with time

Meteorological Service LPN

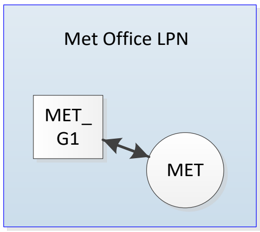

Figure 87 Meteorological Service LPN

Colour type

Colour type	Notation	State Space	Description
MET	$M^{n_2,m_2,t,h}_{ws,xMET}, M^{n_2,m_2,t,h}_{ws,y,MET}$	$\mathbb{R}_+$	Forecast matrix of the environment's wind speed along x and y-direction
	$M^{n_1,m_1,t}_{wx,MET}$	$\{true, false\}$	Forecast matrix of the environment's weather phenomena. The airspace that the phenomena take place is considered unavailable.
	$M^{i,t}_{AP,MET}$	$[0,5]$	Forecast matrix of the Airports' weather phenomena

Colour function

Place	Colour type	Colour function
MET_P1	MET	$dt^{MET}_{timer} = -dt$

Initial marking

Place	Initial Colour
MET_P1	A token with colour MET

Guard transitions

Transition	Guard Condition	Firing function
MET_G1: MET_P1→ MET_P1	$t^{MET}_{timer} \leq 0$	A token with colour MET: $M^{n_2,m_2,t,h}_{ws,xMET} = w^{n_2,m_2,t,h}_{x,EN} + w^{n_2,m_2,t,h}_{x,EN} \cdot N(\mu^{er}_{w}, \sigma^{er}_{w}, l^{er}_{w}, u^{er}_{w})$ $M^{n_2,m_2,t,h}_{ws,yMET} = w^{n_2,m_2,t,h}_{y,EN} + w^{n_2,m_2,t,h}_{y,EN} \cdot N(\mu^{er}_{w}, \sigma^{er}_{w}, l^{er}_{w}, u^{er}_{w})$ $M^{n_1,m_1,t}_{wx,MET} = W^{i,t}_{AP}$

		$Wx = random[1,2,3,4,5]$
		$for\ t<10800: M_{AP,MET}^{i,t} = A_{wx}^{n_1,m_1,t}$
		if 10800<t<21600:
		for 900 consecutive t
		$If\ M_{AP,MET}^{i,t} = 0 : M_{AP,MET}^{i,t} = Wx, with$ probability $P_{A,met1}$
		$If\ M_{AP,MET}^{i,t} > 0 : M_{AP,MET}^{i,t} = 0, with$ probability $P_{A,met1}$
		if 21600< t<30600:
		for 900 consecutive t
		$If\ M_{AP,MET}^{i,t} = 0 : M_{AP,MET}^{i,t} = Wx, with$ probability $P_{A,met2}$
		$If\ M_{AP,MET}^{i,t} > 0 : M_{AP,MET}^{i,t} = 0, with$ probability $P_{A,met2}$
		if t>30600:
		for 900 consecutive t
		$If\ M_{AP,MET}^{i,t} = 0 : M_{AP,MET}^{i,t} = Wx, with$ probability $P_{A,met3}$
		$If\ M_{AP,MET}^{i,t} > 0 : M_{AP,MET}^{i,t} = 0, with$ probability $P_{A,met3}$
		Used variables from other LPNs:
		• $w^{n_2,m_2,t,h}$, $A_{wx}^{n_1,m_1,t}$ from EN
		• $W_{AP}^{i,t}$ from AP_WX

Parameters

Parameters	Description	Value	Explanation
t_{timer}^{MET}	Timer for receiving weather information from the environment and producing the new weather forecast report	1800 s	Time of weather information update (METAR publish period) [1]
$P_{A,met1}$	Probability of en-route weather forecast mistake (short forecast)	0.0001	It was assumed that 1 every 10000 weather forecasts may be mistaken for short term airport weather forecast
$P_{A,met2}$	Probability of en-route weather forecast mistake (medium forecast)	0.001	It was assumed that 1 every 1000 weather forecasts may be mistaken for short term airport weather forecast
$P_{AP,met3}$	Probability of airport weather forecast mistake (long forecast)	0.005	It was assumed that 5 every 1000 weather forecasts may be mistaken for short term airport weather forecast
$\mu_w^{er}, \sigma_w^{er}, l_w^{er}, u_w^{er}$	Truncated normal distribution parameters for wind forecast error	$0, \frac{5t}{3600}, \frac{-10t}{3600}, \frac{10t}{3600} ms^{-1}$	It is assumed that the wind forecast error is a time-dependent error which follows a truncated normal distrib.

[1] https://www.skybrary.aero/index.php/Weather_Observations_at_Aerodromes

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

None.

Incoming arcs from other agents

There are incoming arcs to MET LPN from EN and AP

- EN provides information related to the environment's weather.
- AP provides information related to airports weather.

Outgoing arcs to other agents

There are outgoing arcs to Flight Crew PL and SA, and Airlines Dispatch.

- Flight Crew PL receives the weather forecast (en-route and airport).
- ATCo_SA is being updated throughout the flight about the airport and en-route weather.
- Airline dispatch receives the wind forecast.

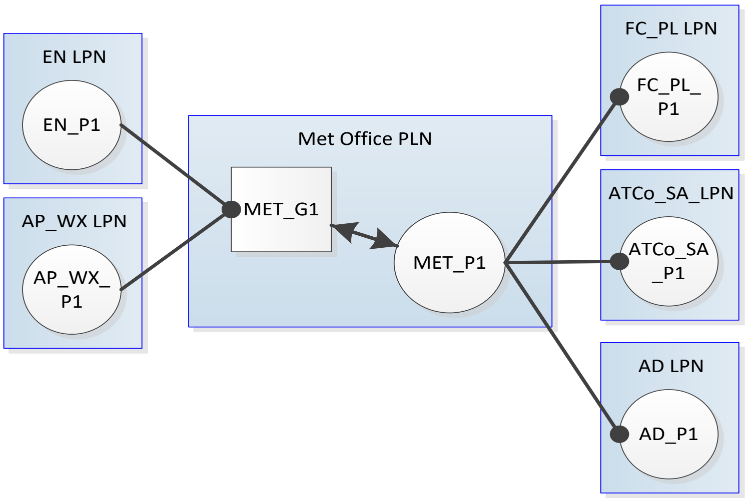

Figure 88 MET Office LPN interactions

D.15 NOTAM Office agent (NOTAM)

Assumptions

1. It is assumed that when a NOTAM sets a sector as unavailable, the entire airspace of the sector (all altitudes) becomes unavailable.

NOTAM LPN

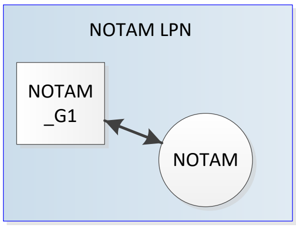

Figure 89 NOTAM LPN

Colour type

Colour type	Notation	State Space	Description
NOTAM	$A_{2,NOTAM}^{n_2,m_2,t}$	$\{true,\ false\}$	Airspace Sectors S_2 availability
	$A_{3,NOTAM}^{n_3,m_3,t}$	$\{true,\ false\}$	Airspace Sectors S_3 availability

Colour function

Place	Colour type	Colour function
NOTAM_P1	NOTAM	$dt_{timer}^{NOTAM} = -dt$

Initial marking

Place	Initial Colour
NOTAM _P1	A token with colour NOTAM

Guard transitions

Transition	Guard Condition	Firing function
NOTAM_G1: NOTAM_P1→ NOTAM_P1	at pre-flight OR $t_{timer}^{NOTAM} \le 0$	A token with colour NOTAM: $A_{2,NOTAM}^{n_1,m_1,t} = A_{2,EN}^{n_2,m_2,t}$ $A_{3,NOTAM}^{n_3,m_3,t} = A_{3,EN}^{n_3,m_3,t}$ Used variables from other LPNs: • $A_{2,EN}^{n_2,m_2,t}, A_{3,EN}^{n_3,m_3,t}$ from EN

Parameters

Parameters	Description	Value	Explanation
t_{timer}^{NOTAM}	Timer for updating the information and publishing the new NOTAM	3600s	It was assumed that the NOTAM office publishes NOTAMs once every hour.

Incoming arcs within the same agent

None.

Outgoing arcs within the same agent

None.

Incoming arcs from other agents

There are incoming arcs to MET LPN from EN and AP

- EN provides the NOTAM office with the current situation of the environment.

Outgoing arcs to other agents

There are outgoing arcs to FC_PL and ATCo_SA, and AD.

- Flight Crew PL receives the NOTAM about the airspace availability.
- ATCo SA is being updated throughout the flight about the airspace availability through the NOTAMs.
- Airline dispatch AD receives the NOTAM about the airspace availability.

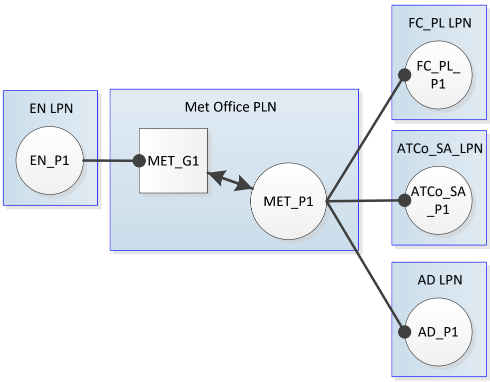

Figure 90 NOTAM agent interactions