EPISODE 3

Single European Sky Implementation support through Validation

Document information	
Programme	Sixth framework programme Priority 1.4 Aeronautics and Space
Project title	Episode 3
Project N°	037106
Project Coordinator	EUROCONTROL Experimental Centre
Deliverable Name	Method for Systematic Risk Assessment for Units of Operation
Deliverable ID	D2.4.3-04
Version	1.01
Owner	
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Contributing partners	
AENA, CAST, DFS, ERC, INECO, NATS, NLR	

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Version history

Version	Date	Status	Author(s)	Justification - Could be a reference to a review form or a comment sheet
1.00	23/09/2009	Approved	Eric PERRIN Brian HICKLING	Document approved by the EP3 Consortium.
1.01	24/09/2009	Approved	Catherine PALAZO	Minor format changes

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EXECUTIVE SUMMARY

Since 2004, EUROCONTROL has constructed an Integrated Risk Picture (IRP), showing the overall contribution of Air Traffic Management (ATM) to aviation accident risks, and highlighting possible interdependencies[1], so that the priorities for safety improvements can be identified in a systematic way.

(**Ref 1**) explains how the Integrated Risk Picture (IRP) can be used to quantify the accident risks in the SESAR Concept of Operations, thereby supporting a systemic risk assessment of SESAR.

The present study develops the IRP predictive mode to represent individual ATM units such as airports, airspaces, countries or individual flights. This addresses two specific needs:

- The safety assessment of SESAR is broken down into three main flight phases (airport, terminal and en-route). It is desirable for IRP to deliver results following the same breakdown.
- Individual ANSPs require risk information for their airspaces that is consistent with EUROCONTROL's requirements for ECAC airspace as a whole. It is therefore desirable for IRP to deliver results for any ANSP.

For EP3 WP2.4.3, a comprehensive methodology for a unit-specific IRP has been developed. This enables to apportion all parts of the IRP fault tree model into generic airspace types, which can then be used to estimate the risk picture for any specific ATM unit. By checking the results against the original data, it is possible to verify that there are no obvious errors in the airspace-specific model construction.

In order to represent the characteristics of individual ATM units in more detail, an extensive set of influences has also been considered, and quantified where possible. This model in effect extends the existing IRP influence model to cover the main influences of the operating environment that are expected to vary between ATM units. However, due to a lack of suitable data, this unit-specific influence model necessarily makes extensive use of assumptions that at present cannot be validated. Its results are therefore extremely uncertain.

This report presents the methodology and some example results. This will help show whether the results have face validity, and so the report is a first step towards improving confidence in the model.

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[1] The model captures some interdependencies that are "true" in the sense that are objectively verifiable links between ATM elements, and some interdependencies that are deduced from historical risk patterns. It then applies them to current and future operations, in order to predict the most important ones. That is what is meant by "highlighting possible interdependencies".

1 INTRODUCTION

1.1 BACKGROUND

Since 2004, EUROCONTROL has constructed an Integrated Risk Picture (IRP), showing the overall contribution of Air Traffic Management (ATM) to aviation accident risks, and highlighting possible interdependencies, so that the priorities for safety improvements can be identified in a systematic way.

The IRP is based on a model of risks in gate-to-gate operations, which can represent a future concept of operations for ATM. With a particular emphasis on ATM contributions (both positive and negative), it reflects the relationships between accidents and incidents taking due consideration of ATM scope, functions and boundaries. It also, together with uncertainty analyses, predicts what the frequencies of accidents and incidents and the different types of causal breakdowns, would be for any given situation with a future concept of operations for ATM, if that future concept of operations for ATM were properly specified from a safety perspective and implemented in accordance with that specification[2].

Since 2006, a methodology has been developed for a Safety Target Achievement Roadmap (STAR), which shows the risks during the implementation of this concept of operations, i.e. the transition from the present towards the future vision. A specific version of IRP has been developed, known as a STAR tool, which will generate the STAR as the concept of operations is finalised.

(**Ref 1**) explains how the Integrated Risk Picture (IRP) can be used to quantify the accident risks in the SESAR Concept of Operations, thereby supporting a systemic risk assessment of the SESAR concept as a whole.

To date, IRP has represented European ATM as a whole, and it is now desirable to break down the results to provide risk predictions for individual ATM units such as airports, airspaces, countries or individual flights. This requirement is addressed in (**Ref 1**) and the selected methodology is described in this report.

1.2 OBJECTIVES

The objective of this report is to develop the IRP predictive mode to represent individual ATM units such as airports, airspaces, countries or individual flights. This can therefore be seen as a type of apportionment of risks by ATM unit.

This capability, once validated, will address two specific needs:

- The safety assessment of SESAR is broken down into three main flight phases (airport, terminal and en-route). It is desirable for IRP to deliver results following the same breakdown.
- Individual ANSPs require risk information for their airspaces that is consistent with EUROCONTROL's requirements for ECAC airspace as a whole. It is therefore desirable for IRP to deliver results for any ANSP.

These key requirements have been used to guide the approach and level of detail adopted in the work.

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[2] Data-based, static models such as IRP, whilst providing a useful view of how ATM contribution to safety could look in the future, cannot provide assurance that it will actually look like that in practice, since the latter requires more direct, and for some purposes more dynamic, representations of safety contribution through the specification, modelling and simulation of the safety properties (functionality, performance, reliability and integrity) of the future ATM system.

1.3 CHOICE OF APPROACH

The IRP fault tree model has been developed to represent an average of flights in the ECAC region (**Ref 1**). In principle, the risk in any given airspace type should be obtained from a specific model of that situation. The risk in units that combine airspace types could then be obtained by summing the results from the separate models. In practice, this would be quite complex, especially if combined with variations in other parameters. Therefore, the IRP uses a simplified approach consisting of a single model, which is modified to represent any given airspace type or combination of types. Any modified version of the model has the exactly the same structure as the generic average one, but different event probabilities.

The airspace-specific capability can be seen as an apportionment of the overall model by airspace types. Strictly, it is only the event frequencies that are apportioned; as these should always sum to the total frequencies that are represented in the generic model. This is verified in Section 5 below. The barrier failure probabilities and influence model parameters are modified to apply to the specific airspace; and their values are constrained to average to the values that are represented in the generic model. This results in two different combination methodologies, as follows.

The main advantage of this approach is that it allows a single instance of the risk model to be used, which is convenient and simple. It also ensures that incremental changes in the proportions of airspace produce smooth changes in the risk picture. For example, each model parameter for an ATM unit with a greater proportion of flight time in upper airspace than ECAC average will always be between the generic average and the value for upper airspace alone.

A disadvantage is that the approach constrains some of the parameters so that they cannot all be based directly on data. However, these errors are considered minor compared to the uncertainties in establishing the parameters of the airspace-specific model.

1.4 LIMITATIONS OF UNIT-SPECIFIC MODELS

Individual airspaces differ from each other in many ways, and these differences are likely to result in different risk pictures. For example, it is clear that not all terminal airspace is the same, and in reality different terminal airspaces will inevitably have different risk pictures. The differences are much more complex than those arising from the generic type of airspace.

In principle, quantification of the risk picture for a specific airspace could be based on local accident/incident data. In practice, there would be many difficulties in this. For a start, few airspaces are large enough to have sufficient incident experience to quantify more than the highest contributors to the lowest levels of the fault tree. In addition, many differences that might appear between local data and the average represented in IRP are likely to result from differences in data quality or reporting thresholds, as well as from the fact that IRP itself is not based on a truly representative European dataset, but on a selection of data from countries that investigate and report incidents in the public domain and in English. Hence, even this "ideal" approach might not give a meaningful differences compared to the average represented in IRP.

Many features of specific airspaces are truly individual, reflecting purely local patterns of traffic and infrastructure, offering no particular insight into any other airspace. It would be unrealistic to expect a risk model such as IRP to predict the risks arising from such effects.

Consider this example: VFR infringement frequencies vary across Europe, and therefore every ANSP will have a local frequency that differs from the ECAC average. This is the reason why NATS experience would differ from a generic IRP, even if all incidents were reliably captured and reported. Some of the causes of these variations may be predicted from available data, say the amount of VFR traffic in each state. This is what the unit-specific IRP tries to do. But other causes of variations are unique to the state, e.g. the fact that the UK has many small airfields in the same part of the country as its main commercial airports. It is impossible for a unit-specific model to predict such factors. We cannot assume that they are small.

The best that a unit-specific risk model can be expected to do is to represent the main features that vary between airspaces, in so far as they can be quantified, using simple measures that can be related to risk levels or individual causal factors.

Indeed the unit (or airspace) –specific capability can be seen as an apportionment of the overall ECAC-wide generic model. This is what the IRP unit-specific model attempts to do, as described below.

As a result, the unit-specific model is not (and cannot be) a prediction of risks in specific airspaces. Rather, it is a prediction of the risks that are expected to arise from the combination of quantifiable influences that are known to be present in the specific airspace. Although this sounds like a minor difference, it may account for very large differences between the unit-specific model and local incident statistics.

1.5 INTENDED READERSHIP

This document is aimed mainly at safety practitioners, in particular specialist analysts who may wish to comment on the proposed method. The whole report is aimed at people who already understand the basis for IRP, and consequently, it should be read in conjunction with D2.4.3-02 (SESAR Top-Down Systemic Risk Assessment) (**Ref 1**), especially the methodological section of (**Ref 1**).

1.6 REPORT STRUCTURE

The present report explains the methodology that has been adopted for the unit-specific IRP.

Section 2 explains the choice of generic airspace types and flight phases that are used in the model. These may be combined in appropriate proportions to represent any ATM unit.

Section 3 explains how the quantitative fault tree model is apportioned into the different generic airspace types and flight phases, and how they can be combined to represent an ATM unit.

Section 4 explains how the influences of specific airspaces can be quantified, to make the results reflect the characteristics of any individual ATM unit.

Section 5 verifies that the model has been constructed correctly, by comparing the results to available data on mid-air collision frequencies in the generic airspace types.

Section 6 presents results for example ATM units.

Section 7 summarises the work and presents recommendations for risk reduction and model improvements.

2 GENERIC AIRSPACE TYPES

2.1 REQUIREMENTS

The required capability is to obtain risk predictions and causal breakdowns for specific cases, which may be:

- Countries within the ECAC region
- ANSPs
- Airspace control centres such as MUAC
- Airspaces ranging from large functional airspace blocks (FAB) to individual sectors
- Airports
- Individual flights between airport pairs (or to the border of the ECAC region)

The distinctive feature of these cases is that they cover a range of ATM elements, but each comprises only a small part of overall ECAC airspace and flight exposure.

In order to achieve this, the overall ECAC airspace that is represented in IRP must be broken down into some generic airspace types, which can be combined in various proportions to represent the required cases above. These generic airspace types must be suitable to categorise both flight exposure and accident/incident experience.

The following generic airspace types have been selected:

- Upper airspace
- Lower airspace
- Terminal airspace, including terminal manoeuvring areas (TMA)
- Airport airspace, including control areas (CTA)
- Uncontrolled airspace[3]
- Temporary airspace

These generic airspace types are explained in turn below.

2.2 DEFINITION OF AIRSPACE TYPES

2.2.1 Upper Airspace

Upper airspace is controlled airspace used mainly by jets in the cruise flight phase. In Europe, the Upper Information Region (UIR) is defined as airspace above a division level (generally FL195). It may vary in different countries. Maastricht Upper Area Control Centre (MUAC) covers airspace above FL245 in Belgium, the Netherlands, Luxembourg and NW Germany. In the USA, UIRs are not used, but high altitude en-route sectors typically begin at FL240.

Upper airspace is controlled through area control centres (ACC) in Europe or ATC centres (ATCC) in the USA. Categorisation varies, e.g. Class C in most of ECAC; Class B in the UK until 2006; and Class A in the USA.

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[3] This will be known as unmanaged airspace in SESAR.

In the present work, when categorising separation incidents, upper airspace is defined as airspace above a division level if defined, or above FL195 otherwise.

2.2.2 Airport Airspace

Airport airspace consists of volumes of controlled airspace around small and medium sized airports. A control zone (CTR) extends from the ground to a specified limit, typically 2000-5000ft. A control area (CTA) is usually situated on top of a control zone, and provides protection for aircraft climbing from an airport. Airport airspace is controlled by airport towers (TWR).

In the present work, when categorising separation incidents, airport airspace is defined as CTA or CTR, or under TWR control otherwise. At present this includes TWR control after flights through TMAs. Final approaches at uncontrolled airports are included under uncontrolled airspace.

2.2.3 Terminal Airspace

Terminal manoeuvring areas (TMA) or terminal control areas (TCA) are volumes of controlled airspace around one or more large airports where several airways converge. They are large versions of airport CTAs. Extended terminal manoeuvring areas (ETMA) are used for complex airports, and consist of the en-route airspace surrounding the TMA, from the top of descent to the initial approach fix.

Terminal airspace is a concept developed for the present study, consisting of the TMA/TCA/ETMA outside the airport airspace (see above).

Terminal airspace may be controlled by approach control (APP) or terminal radar approach control (TRACON) in the USA.

2.2.4 Lower Airspace

Lower airspace consists of controlled airspace below the division level and outside the terminal or airport airspace. It includes airways linking the airport with upper airspace. Lower airspace is controlled through area control centres (ACC) in Europe or ATC centres (ATCC) in the USA.

In the present work, when categorising separation incidents, lower airspace is defined as controlled airspace below a division level if defined, or below FL195 otherwise, and outside terminal or airport airspace (as defined above).

2.2.5 Uncontrolled Airspace

Uncontrolled airspace[4] is defined as Class F and G airspace. It includes all airspace not otherwise categorised.

2.2.6 Temporary Airspace

Temporary airspace is defined as airspace that is sometimes available for commercial aircraft and sometimes reserved for other activities. It includes temporary reserved areas (TRAs) or temporary segregated areas (TSAs). These may include military training areas (MTAs).

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[4] To be renamed unmanaged airspace in SESAR.

2.2.7 Oceanic Airspace

Oceanic airspace consists of airspace that is mainly out of range of land-based radar surveillance and VHF communication, and hence has special procedures associated with it.

It is outside ECAC airspace, and hence is outside the scope of IRP at present. Separation incidents in oceanic airspace are therefore neglected.

2.3 BREAKDOWN OF FLIGHT TIME BY AIRSPACE TYPE

2.3.1 Data and Assumptions

The breakdown of flight time by airspace type is critical for many of the risk results in the unit-specific IRP. It would be desirable to obtain ECAC average data on this, but none has been identified for the present study. In its absence, the following estimates are made based on data from Boeing on times in different flight phases (**Ref 2**). Definitions of these flight phases are provided in Section 2.4 below. This data is combined with estimates and assumptions about the links between flight phases and airspace types. In the absence of complete ECAC data, some estimates are based on available data for the UK. The data sources and assumptions are presented below in full.

2.3.2 Upper Airspace

Large jets spend on average 57% of a typical 1.5 hour flight in the cruise phase (**Ref 2**). In the present study, this is assumed to occur in upper airspace and to apply to all jet traffic. It may be lower in Europe, but no data is known. Jets account for 71% of commercial flights (based on data on Western commercial aircraft world-wide during 1990-2006). This may be higher in Europe, but no data is known. Overall, flight exposure in upper airspace is estimated as 40% of the total for commercial flights.

2.3.3 Airport Airspace

Large jets spend on average 6% of a typical 1.5 hour flight in take-off, initial climb, final approach and landing phases (**Ref 2**). In the present study, this is assumed to occur in airport airspace and to apply to all commercial traffic. Overall, flight exposure in airport airspace is estimated as 6% of the total for commercial flights.

2.3.4 Terminal Airspace

Large jets spend on average 37% of a typical 1.5 hour flight in climb, descent and initial approach phases (**Ref 2**), of which 35% is in controlled airspace (see below). In the present study, this is assumed to apply to all commercial traffic. The 4 UK TMAs (London, Manchester, Belfast and Scottish) have approximately 65% of UK commercial movements (based on CAA data for 2005). This is assumed to apply to Europe as a whole. Overall, flight exposure in terminal airspace is estimated as 23% of the total for commercial flights.

2.3.5 Lower Airspace

Flight exposure in lower airspace includes:

- The cruise phase on turboprops. This amounts to 57% of flight time for 29% of flights (based on the calculations for upper airspace).
- The climb, descent and initial approach phases, where these do not occur in terminal or uncontrolled airspace. This amounts to 35% of flight time for 35% of flights (based on the calculations for other airspace types).

In total, this is 29% of the total for commercial flights.

2.3.6 Uncontrolled Airspace

In the UK, the structure of airspace is such that any flight to Bristol, Derry, Durham Tees, Exeter, Inverness, Isles of Scilly, Kirkwall, Lerwick, Lands End, Newcastle, Plymouth, Sumburgh or Wick must pass through uncontrolled airspace. Other flights may choose to do so too. The above airports have approximately 9% of UK commercial movements (based on CAA data for 2005). The UK is assumed to be typical of Europe as a whole in this respect. It is assumed that only the descent and initial approach are in uncontrolled airspace, amounting to 23% of the flight (**Ref 2**). This is 2% of the total for commercial flights.

2.3.7 Temporary Airspace

In the absence of any data, it is assumed that 1 in 100 flights of commercial aircraft pass through temporary airspace at present, although this may increase substantially in SESAR. It is assumed that these flights spend 10% of their flight time in such airspace, giving a total of 0.1% of the flight time for all aircraft.

The risks in temporary airspace are considered to relate more to the number of entries than the length of time inside the airspace, so for simplicity the flight time in temporary airspace could be treated as part of the cruise flight phase in upper airspace.

2.3.8 Results

The above methodology is summarised in Figure 1. This also includes the more detailed flight phase breakdown from Section 2.4. The resulting estimated flight exposure breakdown for commercial aircraft in Europe is summarised in Table 1.

Figure 1: Commercial Flight Exposure Breakdown by Airspace

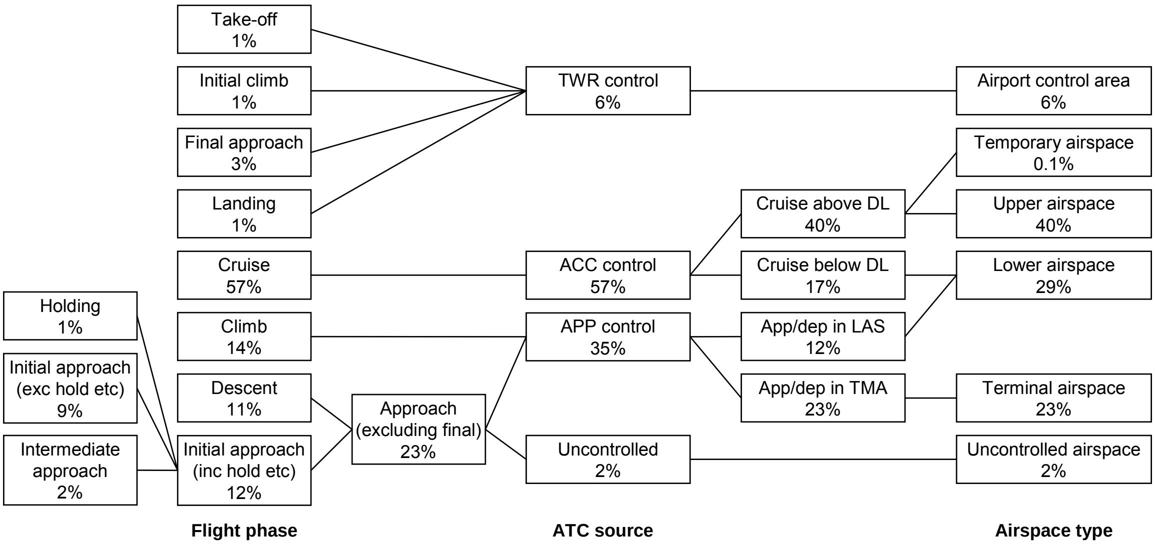

Table 1: Commercial Flight Exposure Breakdown by Airspace

AIRSPACE TYPE	EXPOSURE (% of flight)	EXPOSURE (hours per flight)
Upper airspace	40%	0.60
Lower airspace	29%	0.44
Terminal airspace	23%	0.35
Airport airspace	6%	0.09
Uncontrolled airspace	2%	0.03
Temporary airspace	0.1%	0.001
TOTAL	100%	1.50

2.4 BREAKDOWN OF FLIGHT TIME BY FLIGHT PHASE

2.4.1 Data and Assumptions

The breakdown of flight time by flight phase is another critical input to the unit-specific IRP. As with airspace types, it would be desirable to obtain ECAC average data on this, but none has been identified for the present study. In its absence, the following estimates are made based on world-wide data (**Ref 2**), combined with assumptions about flight phases not distinguished in that source. The data sources and assumptions are presented here in full.

2.4.2 Taxi

In IRP, the taxi phase consists of the following sub-phases, which are not separately quantified at present:

- Push-back - aircraft reversed from the gate or parking position using tug/tow vehicle.
- Taxi-out - aircraft movement under its own power from the gate or parking position or push-back position to the runway take-off position.
- Taxi-in - aircraft movement under its own power from the runway exit point to the gate or parking position.
- Tow - aircraft movement between the gate, parking position and/or hangar using tug/tow vehicle.

This definition is consistent with the ECCAIRS/ADREP term “taxi” (**Ref 3**), and equivalent to the CAST/ICAO terms “taxi” and “pushback/tow” (**Ref 4**).

Strictly, taxi is not a flight phase, and it is not included in most flight time estimates. However, it is a significant part of the gate-to-gate cycle, so it is included here.

In the absence of any useful data, the average taxi time is assumed to be 15 minutes per flight. This is a 16.7% addition to a 1.5 hour flight.

2.4.3 Take-Off

In IRP, the take-off phase includes:

- Take-off run - from application of take-off power to 35 ft above runway.
- Aborted take-off - take-off terminated after application of take-off power.

This definition is consistent with the CAST/ICAO term “take-off” (**Ref 4**). It contrasts with the ECCAIRS/ADREP terms “take-off” (**Ref 3**), which includes climb, and “take-off run”, which extends to 50ft above the runway. This is less appropriate for a risk model, because it is more similar to the climb phase.

The Boeing data (**Ref 2**) indicates 1% of a flight is in take-off. This is equivalent to 1 minute in a 1.5 hour flight.

2.4.4 Initial Climb

In IRP, the initial climb phase extends from 35 ft above the runway to 1500 ft, or the first power reduction if this occurs earlier.

This definition is similar to the ECCAIRS/ADREP term “initial climb” (**Ref 3**), which begins from 35ft, and the CAST/ICAO term “initial climb” (**Ref 4**), which extends to 1000ft above the runway or the VFR pattern if this occurs earlier. The differences are not very important because the phase is difficult to distinguish from climb to cruise, and could be combined with it in future work.

The Boeing data (**Ref 2**) indicates 1% of a flight is in initial climb. This is equivalent to 1 minute in a 1.5 hour flight.

2.4.5 Climb to Cruise

In IRP, the climb to cruise phase extends from the end of the initial climb to the first assigned cruise level (i.e. the top of climb).

This definition is similar to the Boeing term “climb (flaps up)” (**Ref 2**), the ECCAIRS/ADREP term “climb into traffic pattern” (**Ref 3**) and the CAST/ICAO term “climb to cruise” (**Ref 4**).

The Boeing data (**Ref 2**) indicates 14% of a flight is in climb (flaps up). This is equivalent to 13 minutes in a 1.5 hour flight.

2.4.6 Cruise

In IRP, the cruise phase includes:

- Cruise - from top of climb to top of descent.
- Change of cruise level - from one cruise flight level to another.

This definition includes the same two sub-phases in the CAST/ICAO and ECCAIRS/ADREP “en-route” phases (**Ref 3** & **Ref 4**), which also include climb to cruise, descent and holding.

The Boeing data (**Ref 2**) indicates 57% of a flight is in cruise. This is equivalent to 51 minutes in a 1.5 hour flight.

2.4.7 Descent

The descent phase extends from the end of the final assigned cruise level (i.e. the top of descent) to the initial approach fix, final approach fix, outer marker, 1500ft above runway or entry to the VFR pattern, whichever occurs first.

This definition is taken from the ECCAIRS/ADREP term “normal descent” (**Ref 3**), and is similar to the CAST/ICAO term “descent” (**Ref 4**).

The Boeing data (**Ref 2**) indicates 11% of a flight is in descent. This is equivalent to 10 minutes in a 1.5 hour flight.

The end of the descent phase depends on the specific fixes in the approach layout, and available accident reports are sometimes insufficient to determine whether these fixes have been reached. In cases with no better information, it is assumed that flight levels above the transition altitude (18,000 ft in the USA or lower elsewhere) indicate the aircraft is in the descent phase.

2.4.8 Holding

The holding phase consists of a pre-determined manoeuvre (usually an oval race track pattern) that keeps the aircraft in a specified airspace while awaiting further instructions. Holding typically occurs at the initial approach fix, and is typically associated with further descent.

This definition is consistent with ECCAIRS/ADREP (**Ref 3**), in which it may be part of the en-route or approach phases, and CAST/ICAO (**Ref 4**), in which it is part of the en-route phase.

In the absence of any data, holding is assumed to last 5 minutes on 20% of flights, equivalent to an average of 1% of flight time.

2.4.9 Initial Approach

In IRP, the initial approach phase extends from the from initial approach fix to the intermediate approach segment, if flown, or the final approach fix otherwise.

This definition covers part of the ECCAIRS/ADREP and CAST/ICAO terms “initial approach”, which include any intermediate approach segment (**Ref 3** & **Ref 4**).

The Boeing data (**Ref 2**) indicates 12% of a flight is in initial approach, but after excluding holding and intermediate approach, this is reduced to 9%. This is equivalent to 8 minutes in a 1.5 hour flight.

2.4.10 Intermediate Approach

In IRP, the intermediate approach phase may extend from a middle approach fix or the end of a reversal turn procedure to the final approach fix.

This definition is taken from ECCAIRS/ADREP (**Ref 3**). It is not used by CAST/ICAO (**Ref 4**).

In the absence of any data, intermediate approach is assumed to last 4 minutes on 50% of flights, equivalent to an average of 2% of flight time.

Flight phases on approach depend on the specific fixes in the approach layout, and available accident reports are sometimes insufficient to determine which phase was applicable. In cases with no better information, the following simplifying assumptions are made:

- In a vectored approach, intermediate approach is from the first ATC instructed course change to the glideslope intercept.
- In a reversal procedure, the initial approach is prior to the reversal turn, and the intermediate approach is between the reversal turn and the glideslope.
- In a straight-in approach, the initial approach is from the outer marker to the glideslope, and there is no intermediate approach.

2.4.11 Final Approach

In IRP, the final approach phase extends from the final approach fix to the landing flare.

This definition is taken from CAST/ICAO (**Ref 4**) and is consistent with ECCAIRS/ADREP (**Ref 3**).

The Boeing data (**Ref 2**) indicates 3% of a flight is in final approach. This is equivalent to 3 minutes in a 1.5 hour flight.

The final approach phase depends on the specific fixes in the approach layout, and available accident reports are sometimes insufficient to determine whether it has been reached. In cases with no better information, it is assumed that final approach is within 6nm distance or 1600ft height above the runway.

2.4.12 Landing

In IRP, the landing phase includes:

- Flare - the transition from nose-low to nose-up just before touchdown.
- Touchdown - from flare to touchdown on runway.
- Landing roll - from touchdown to runway exit.

This definition is taken from CAST/ICAO (**Ref 4**) and is consistent with ECCAIRS/ADREP (**Ref 3**).

The Boeing data (**Ref 2**) indicates 1% of a flight is in landing. This is equivalent to 1 minute in a 1.5 hour flight.

2.4.13 Missed Approach

In IRP, the missed approach phase extends from the point of terminating the approach to rejoining the initial/intermediate/final approach.

This definition is taken from CAST/ICAO (**Ref 4**) and is consistent with ECCAIRS/ADREP (**Ref 3**).

The current ECAC average missed approach probability is based on British Airways experience in 1997 (**Ref 5**), which is rounded to 5 x 10-3 per flight. In the absence of any data, the duration is assumed to be 10 minutes. This is equivalent to 0.1% of flight time.

2.4.14 Manoeuvring

In IRP, the manoeuvring phase covers any other abnormal operations. These include:

- Low flying - intentional low altitude flight not connected with landing or take-off.
- Aerobatics - training manoeuvres outside the normal flight envelope.
- Touch-and-go training - a landing followed by a take-off without exiting the runway.
- Emergency descent - intentional rapid descent in response to an in-flight emergency.

This definition is consistent with ECCAIRS/ADREP and CAST/ICAO (**Ref 3** & **Ref 4**), after selecting examples applicable to commercial operations.

In the absence of any data, manoeuvring is assumed to have the same frequency and duration as missed approach. This is equivalent to 0.1% of flight time.

2.4.15 Results

Table 2 shows the resulting flight exposure breakdown. The joint distribution of airspace type and flight phase is given in Table 3. This is based on a slightly simplified grouping of flight phases consistent with the Boeing data (**Ref 2**).

Table 2: Commercial Flight Exposure Breakdown by Flight Phase

FLIGHT PHASE	FREQUENCY (phases per flight)	DURATION (min per phase)	EXPOSURE (% of flight time)
Taxi	1	15	16.7%
Take-off	1	1	1.0%
Initial climb	1	1	1.0%
Climb to cruise	1	13	14.0%
Cruise	1	51	57.0%
Descent	1	10	11.0%
Holding	0.2	5	1.1%
Initial approach	1	8	8.6%
Intermediate approach	0.5	4	2.2%
Final approach	1	3	3.0%
Landing	1	1	1.0%
Missed approach	0.005	10	0.1%
Manoeuvring	0.005	10	0.1%
TOTAL (excluding taxi)		90	100%

Table 3: Commercial Flight Exposure Breakdown by Airspace and Flight Phase

AIRSPACE TYPE	Take-off	Initial climb	Climb to cruise	Cruise	Descent	Initial approach	Final approach	Landing	TOTAL
Upper airspace				40%					40%
Lower airspace			5%	17%	4%	4%			29%
Terminal airspace			9%		7%	7%			23%
Airport airspace	1%	1%					3%	1%	6%
Uncontrolled airspace					1%	1%			2%
Temporary airspace				0.1%					0.1%
Total	1%	1%	14%	57%	11%	12%	3%	1%	100%

3 FAULT TREE MODEL OF GENERIC AIRSPACES

3.1 BREAKDOWN OF CAUSAL DATA BY AIRSPACE TYPE

In the case of mid-air collisions, causal investigations involving Western commercial aircraft have been analysed as follows (**Ref 1** – for further details, see section 11.2 in **Ref 1**):

- 12 mid-air collisions world-wide, 1990-2005.
- 24 Airprox incidents in the UK, 2003
- 10 loss of separation incidents in Switzerland, 2003-2004
- 9 loss of separation incidents in Finland, 2000-2003
- 20 loss of separation incidents at MUAC, 2001

Each has been categorised by airspace type, according to the definitions above. Table 4 shows the distribution of events by dataset. Mid-air collisions (MAC) have been split into "large" (i.e. Western commercial jets above 27 tonnes MTOW) and "other" (i.e. commercial turboprops and smaller jets), because they have different airspace breakdowns.

Table 4: Separation Incident Breakdown by Airspace

AIRSPACE TYPE	Large MAC	Other MAC	UK Airprox	Swiss incidents	Finnish incidents	MUAC incidents	TOTAL
Upper airspace	2		1	4	1	20	28
Lower airspace	2	1	3		1		7
Terminal airspace			10	4	7		21
Airport airspace	1		3	2			6
Uncontrolled airspace	1	5	6				12
Oceanic airspace			1				1
Total	6	6	24	10	9	20	75

The different ANSPs also show different airspace breakdowns. At present it is assumed that the combination of all data provides a representative sample of separation incidents in ECAC. However, the data are reported incidents and as such may also inherently reflect differences in reporting rates. In the future, a larger dataset covering more countries would be desirable for future work[5].

The dataset does not include any events in temporary airspace, so it is not possible to obtain risks there from this source. The dataset does include one event in oceanic airspace, which is eliminated in the following analysis. In future work, it would be preferable to include more such incidents, so as to develop the capability of modelling this type of airspace.

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[5] During the SESAR Development Phase, it is proposed that the first step for Project P16.1.1 will be to enhance the database underpinning the current accident-incident Model with high quality data particularly from ANSPs participating in this project. This will enable an updated model to be developed which is more representative of the diversity of European operations and variations, as well as more sensitive to a broader range of causal factors and operational conditions.

3.2 METHODOLOGY FOR UNIT-SPECIFIC MODIFICATION OF FAULT TREE MODEL

3.2.1 Definition of MF

The parameters of the airspace-specific model consist of modified versions of the overall generic average parameters for ECAC as a whole. The probabilities of the base events of the fault tree are formed using modification factors (MF), defined as:

$$MF = \frac{\text{Base event probability in airspace}}{\text{Generic average base event probability}}$$

Using the terminology from the IRP methodology report [1], the MF is:

$$MF_{i,k} = \frac{P(B_{i,k})}{P(B_i)}$$

Where:

$MF_{i,k}$	=	modification factor for base event i in airspace k
$P(B_{i,k})$	=	probability of base event i in airspace k
$P(B_i)$	=	average probability of base event i

The generic average probability is defined by:

$$P(B_i) = \sum_{k=1}^{K} P(B_{i,k}) E_k$$

Where:

E_k	=	generic exposure (fraction of flight hours) in airspace k
K	=	number of airspace types

3.2.2 Unit-Specific Model for Probabilities

To form the model for a specific airspace unit, consisting of a specific combination of airspace types, the combined MFs for each base event probability are obtained by weighting the MFs for each airspace type by the fraction of flight time in that airspace, as follows:

$$MF_i = \sum_{k=1}^{K} MF_{i,k}\, E_{Ck}$$

where:

E_{Ck}	=	case-specific exposure (fraction of flight hours) in airspace k
MF_i	=	combined modification factor for base event i

The probabilities of other events in the fault tree are formed from these base events using the bottom-up logic of the IRP predictive mode.

Each set of airspace-specific MFs for each base event is constrained so that the average of these MFs, when weighted by the generic exposure in each airspace (from Table 1), is always equal to 1:

$$\sum_{k=1}^{K} MF_{i,k}\, E_k = 1 \qquad \text{For all base events i expressed as probabilities per demand}$$

This ensures that all events in the model return to the average probabilities when ECAC average conditions are selected.

3.2.3 Unit-Specific Model for frequencies

The above approach applies to any event whose units are per demand, i.e. pure probabilities. In the case of events expressed as frequencies with units per flight hour, which are then multiplied by the exposure to obtain the frequency per flight, a different approach is required. To be able to combine such frequencies, they must be in the same units, i.e. frequencies per hour in all airspace types. The frequency per hour in the specific airspace would be a better measure of risk, but would require a unit conversion before different airspace types could be added. Therefore, the combined MF is obtained as follows:

$$MF_i = \sum_{k=1}^{K} P_{i,k}\, EMF_k$$

Where:

EMF_k = exposure modification factor in airspace k

P_{ik} = proportion of base events in airspace k

The exposure modification factor is defined as:

$$EMF_k = \frac{\text{Flight hours per flight in airspace k}}{\text{Generic average flight hours per flight}}$$

By definition, the proportions of events are constrained so that:

$$\sum_{k=1}^{K} P_{i,k} = 1 \qquad \text{For all base events i expressed as probabilities per flight hour}$$

3.3 EXAMPLE MODIFICATION OF MID-AIR COLLISION FAULT TREE MODEL

The MFs are based on the causal data as far as possible. In many cases, probabilities in the fault tree are obtained from a number of failures $N(B_i)$ divided by a corresponding total number of demands N(T). Then the breakdown of this data by airspace gives:

$$P_{i,k} = \frac{N(B_{i,k})}{N(T_k)}$$

Table 5 shows data of this type for the example event of No STCA Coverage. The general pattern in this table, showing greatest coverage in upper airspace and least in airport and uncontrolled airspace, is considered realistic.

Table 5: Effect of Airspace on Probability of No STCA Coverage

AIRSPACE TYPE	MB3.1 EVENTS	ALL EVENTS	MB3.1 PROBABILITY
Upper airspace	2	14	0.14
Lower airspace	4	7	0.57
Terminal airspace	8	21	0.38
Airport airspace	6	6	1.00
Uncontrolled airspace	11	12	0.92
Total	31	60	0.52

However, these probabilities do not satisfy the constraint above that the exposure-weighted average should equal the value of 0.22[6] that is used in the overall fault tree. This is based on information on current STCA coverage, following more widespread fitment in upper, lower and terminal airspace. Therefore the probabilities in these airspace types have been reduced in proportion so that when the required value averaged by exposure is obtained. The necessary adjustment has in this case been determined by an iterative solver since no analytical solution exists. The MFs can then be calculated as follows:

$$MF_{i,k} = \frac{P(B_{i,k})}{\sum_{\mathrm{k}=1}^{\mathrm{K}} P(B_{\mathrm{i,k}})E_{\mathrm{k}}}$$

The resulting probabilities and MFs are shown in Table 6 for the example event MB3.1.

Table 6: Modelled Effect of Airspace on Probability of No STCA Coverage

AIRSPACE TYPE	MB3.1 PROBABILITY	% OF FLIGHT HOURS	MF
Upper airspace	0.07	40%	0.30
Lower airspace	0.26	29%	1.19
Terminal airspace	0.17	23%	0.79
Airport airspace	1.00	6%	4.55
Uncontrolled airspace	0.92	2%	4.17
Total	0.22	100%	1.00

In principle, the same analysis could be conducted for each base event of the fault tree. However, it is recognised that the datasets for most base events are already very small, and hence further subdivision into airspace types tends to give variations that are not statistically significant. Therefore, the variations obtained from the causal data are only included in the model when there is a physical explanation for the difference (e.g. STCA is expected to be less common in uncontrolled and airport airspace in the example above).

3.4 Unit-Specific Modification of Other Fault Tree Models

Other accident categories are modelled in different ways. For runway collision and taxiway collision, all accidents are at the airport by definition, and no airspace-specific breakdown is possible. For CFIT and wake turbulence accident, an airspace-specific breakdown is possible

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[6] This comes from an analysis of STCA coverage by ECAC ACCs, based on ECIP, weighted by controlled flight hours in each ACC.

in principle, but information on airspace type in these events is less detailed than for mid-air collision. Therefore, a simplified approach is used, based on flight phase.

At present, there are too many flight phases and too few accidents/incidents to obtain a breakdown of all fault tree events by flight phase, as was done for airspace type. Instead, a simplified approach is used, in which the event frequencies are based on flight phase data, and the barrier probabilities are assumed independent of flight phase[7].

The modification factors for the frequency base events are obtained in the same way as for the airspace-specific model:

$$MF_i = \sum_{m=1}^{M} P_m \ EMF_m$$

where:

EMFm = exposure modification factor in flight phase m

Pm = proportion of events in flight phase m

M = number of flight phases

The exposure modification factor for flight phase is defined as:

$$EMF_m = \frac{E_{Cm}}{E_m}$$

where:

E_{Cm} = case-specific flight hours per flight in flight phase m (user input)

Em = generic average flight hours per flight in flight phase m (Table 2)

By definition, the proportions of events are constrained so that:

$$\sum_{m=1}^{M} P_{i,m} = 1$$

Table 7 shows the distribution of events by flight phase (Pm) for each accident category except taxi accidents, which are all in the taxi phase by definition. The distributions are based on the sets of accident and incident data used in the causal analysis (**Ref 1**).

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[7] This is an important assumption and the possible sensitivity of the modelling to that assumption will need to be assessed.

Table 7: Breakdown of Accident/Incident Data by Flight Phase

FLIGHT PHASE	MID-AIR COLLISION	RUNWAY COLLISION	CFIT	WAKE ACCIDENT
Taxi	0.0%	40.0%	0.0%	0.0%
Take-off	0.0%	40.0%	0.0%	0.0%
Initial climb	0.0%	0.0%	0.0%	8.1%
Climb to cruise	20.0%	0.0%	6.3%	2.4%
Cruise	39.1%	0.0%	2.1%	16.3%
Descent	17.3%	0.0%	0.0%	16.3%
Holding	7.3%	0.0%	0.0%	0.0%
Initial approach	5.5%	0.0%	12.5%	0.0%
Intermediate approach	5.5%	0.0%	25.0%	8.1%
Final approach	3.6%	0.0%	47.9%	48.8%
Landing	0.0%	20.0%	0.0%	0.0%
Missed approach	0.9%	0.0%	6.3%	0.0%
Manoeuvring	0.9%	0.0%	0.0%	0.0%
TOTAL	100.0%	100.0%	100.0%	100.0%

In order to obtain a flight-phase-specific model, the MFs obtained in this way are applied to the frequency base events in each accident category. These are then combined through the fault tree using the bottom-up predictive mode, to obtain the overall flight-phase-specific risk picture. In order to ensure that these effects are not changed by common causes, the same MFs are also applied to the common cause proportions that have frequencies as an input.

In order to obtain a unit-specific estimate of risks in accident categories other than mid-air collision, the conditional distribution of flight phase for the unit is obtained using the joint probabilities in Table 3. This is then used as the input to the flight-phase specific model above.

4 INFLUENCE MODEL OF SPECIFIC AIRSPACES

4.1 IDENTIFICATION OF INFLUENCES

The first step in developing a unit-specific influence model is to select a set of influences to be quantified. The selected influences should as far as possible be:

- Important, i.e. representing all the main unit-specific influences on accident risks.
- Comprehensible, i.e. readily understood.
- Independent, i.e. not correlated with the other selected influences.
- Quantifiable, i.e. able to be quantified through both accident and exposure data.
- Integratable, i.e. able to be combined with the other influences modelled in IRP.

Identification of influences to represent in the model is based on a combination of:

- Logical identification of factors that are expected to influence the risks.
- Generalisation of factors that are mentioned in incident investigations.
- Factors that are recorded in the ADREP/ECCAIRS taxonomy for accident/incident data.
- Factors that are quantifiable from other available data covering different ECAC airspaces or aircraft operations.

4.2 REPRESENTATION OF INFLUENCES

Several different approaches have been used to represent the influences in the risk model. In declining order of preference, these are:

- Fault tree model. Some of the causal factors that are represented explicitly in the fault tree are likely to vary between units. Although these are not strictly influences, they are included in Table 8 below for completeness.
- Stratified data. If the influences can be stratified (i.e. grouped into states of increasing severity), and the accident/incident and flight exposure data can be stratified in the same way, then modification factors can be calculated for each influence state. However, the relevant data is rarely available.
- Proxy data. If a suitable proxy measure is available for the influence (i.e. a similar or associated metric that can be quantified), it is possible to adopt a relationship between this proxy measure and the selected causal factors in the risk model. Although this relationship is inevitably judgemental, the variation between airspaces (and hence the risk ranking) is then based on data. This approach has the advantage of being able to make use of any available data for different airspaces.
- Performance scores. In the absence of any useful data, the quality of an influence can be related to selected causal factors in the risk model using an assumed relationship, such as the performance score (**Ref 1**). This approach has the advantage of being consistent with other IRP inputs in areas where data is lacking.

The quantification approaches in the unit-specific model for each influence are listed in Table 8 Column 3 of the table shows:

- The modelled states (for stratified influences).
- The proxy metric (for influences based on proxy data).

- The parameter that can be represented as an input to the fault tree (for influences represented in the fault tree).

Table 8 shows the influences that have been identified for possible use in the unit-specific model. In the terminology of the generic IRP influence model (**Ref 1**), they are all constraints of the operating environment, which may differ in different units. At present only influences relating to the en-route phase (i.e. excluding influences of the airport) have been identified. Not all of these have yet been quantified in the IRP (those are parameters followed by a question mark), as data collection is continuing at present. Column 4 of the table indicates where no suitable data has yet been found.

Table 8: Modelled Unit-Specific Influences

INFLUENCE	REPRESENTATION	METRIC/STATES	DATA SOURCE	AFFECTED MODEL PARAMETERS
En-route traffic				
Traffic level	Proxy data	Traffic level (average aircraft per sector)	ACE	ATCO task constraint
Traffic complexity	Proxy data	Aggregated complexity score (minutes of interaction per flight hour)	ACE	ATCO task constraint
Traffic saturation	Proxy data	ATFM en-route delay (minutes of delay per flight hour)	CFMU	ATCO task constraint
Traffic variability	Proxy data	Variability (peak traffic as a fraction of average traffic)	CFMU	ATCO task constraint
Aircraft type	Stratified data	Large jets, props, small jets	CATS	Flight crew performance and aircraft quality
Aircraft size	Stratified data	Heavy, medium, small	CATS	Flight crew performance and aircraft quality
Aircraft generation	Stratified data	First, second, third, fourth	CATS	Flight crew performance and aircraft quality
Aircraft operation type	Stratified data	Passenger, cargo, non-revenue	CATS	Flight crew performance and aircraft quality
Aircraft operator safety management	Proxy data	National income (GDP per capita)	World Bank	Flight crew performance
Military traffic level	Fault tree model	Military flight hours per IFR flight hour?	Not available	MB6.1.1.1 Airspace penetration by military aircraft
Military coordination quality	Performance score		Not available	MB6.1.1.1 Airspace penetration by military aircraft
VFR traffic level	Fault tree model	VFR flight hours per IFR flight hour?	Not available	MB6.1.1.2 Airspace penetration by VFR aircraft
VFR compliance	Performance score		Not available	MB6.1.1.2 Airspace penetration by VFR aircraft
En-route ATM				

INFLUENCE	REPRESENTATION	METRIC/STATES	DATA SOURCE	AFFECTED MODEL PARAMETERS
Airspace type	Stratified data	Upper, lower, terminal, airport or uncontrolled airspace	IRP	All fault tree base events
Airspace design	Performance score	Airspace design quality score	Not available	ATCO task constraint
Airspace boundaries	Proxy data	Handover score (fraction of handovers outside ACC ≈ 1/sectors in ACC)	ACE	ATCO task constraint
Temporary airspace usage	Fault tree model	Temporary airspace entries per IFR flight?	Not available	MB6.1.1.3 Airspace penetration by CAT aircraft
ANSP safety management quality	Proxy data	Compliance score (fraction of safety management harmonisation objectives implemented)	ECIP	ATCO performance and equipment quality
Navigation infrastructure quality	Proxy data	National income (GDP per capita)	World Bank	
ATC system quality	Proxy data	Minutes of ATC equipment-related ATFM en-route delay per flight hour?	CFMU	ATCO task input
Surveillance coverage	Fault tree model	Surveillance coverage	Not available	MB5.1.1.1 Inadequate traffic picture
Surveillance quality	Performance score		Not available	ATCO task input
STCA coverage	Fault tree model	STCA coverage (as a safety net)	Not available	MB3.1 No STCA coverage
STCA performance	Proxy data	Traffic complexity	ACE	MB3.2 STCA fails to give warning in time
Flight plan processing quality	Performance score		Not available	ATCO task input
Traffic sequencing quality	Performance score		Not available	ATCO task input
Natural environment				

INFLUENCE	REPRESENTATION	METRIC/STATES	DATA SOURCE	AFFECTED MODEL PARAMETERS
Light conditions	Fault tree model	Fraction of time flight is in darkness	CATS	MB1.1.1 Other aircraft effectively invisible
Visibility at airport	Proxy data	Minutes of weather-related ATFM en-route delay per flight hour?	CFMU	ATCO taskload (resources)
Visibility in flight	Fault tree model	Fraction of time aircraft is in IMC	CATS	MB1.1.1 Other aircraft effectively invisible
Storm activity	Proxy data	Fraction of flight time with cumulonimbus clouds along aircraft route	Not available	ATCO task constraint

4.3 QUANTIFICATION OF PROXY INFLUENCES

For influences that are represented by proxy data, appropriate proxy measures have been selected based on the available data on area control centres (ACCs) and air navigation service providers (ANSPs) in the ECAC region. This provides the most detailed breakdown by airspace that is currently available. Three key data sources have been used, as shown in Table 8 above:

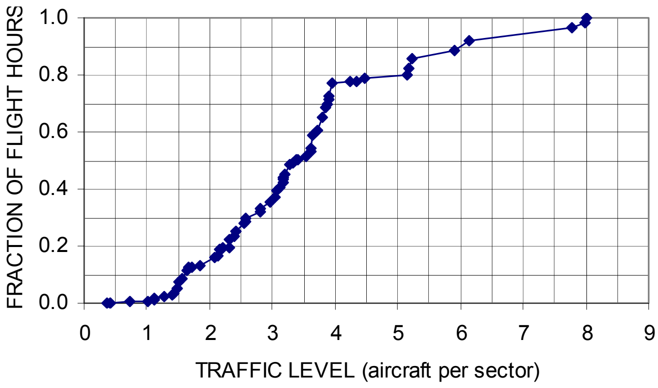
The ATM Cost-Effectiveness (ACE) Benchmarking Report (**Ref 6**). The most recent edition provides data on traffic and complexity at ACC level for 2006.

The CFMU Network Operations Plan (**Ref 7**). The most recent edition provides data on traffic variability and delays at ACC level for 2007.

European Convergence and Implementation Plan (ECIP) (**Ref 8**). The most recent Status Report provides compliance data at ANSP level for 2007.

For each influence, an appropriate proxy measure has been selected. The data sources above define the probability distributions of the selected measures. Figure 2 shows an example distribution for traffic level, defined as the average number of aircraft per sector. In this case, the mean value is 2.9 aircraft per sector, and the 90% range (containing ACCs handling at least 90% of ECAC IFR flight-hours) is 1.5 to 7.8. This is the distribution of average ACC traffic levels. In reality, the distribution of instantaneous sector traffic levels will be wider, but no unit-specific data is available on this at present.

Figure 2: Distribution of ACC Average Traffic Levels



The next step is to non-dimensionalise the proxy by dividing by the average value in ECAC airspace:

$$RL_{j,k} = \frac{L_{j,k}}{L_j}$$

where:

$RL_{j,k}$	=	relative level of proxy metric for influence j in airspace k
$L_{j,k}$	=	level of proxy metric for influence j in airspace k
L_j	=	generic average level of proxy metric for influence j

In the example above, the relative level of traffic ($RL_{traffic}$) is equal to the traffic level (in units of aircraft per sector) divided by 2.9 (i.e. the average level).

Table 8 shows the model parameters that are assumed to be affected by the proxy measure. Without stratified data, it is virtually impossible to validate this choice.

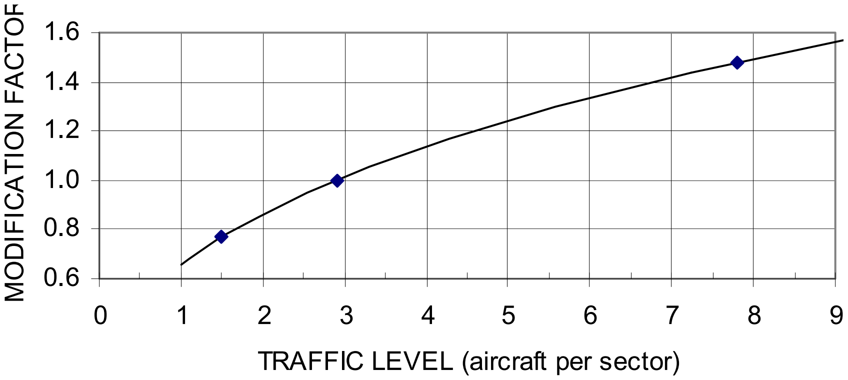
A relationship must then be assumed between the metric and the modification factor for selected base events or influences in the model:

$$MF_{i,j,k} = f(RL_{j,k})$$

The average values of RL and MF across all airspaces should be 1 in all cases, as in Section 3.2. A functional relationship is easily constrained so that the medians are 1, but it would be more difficult to ensure that the means of the distributions are 1, and this is not verified at present. The proxy model is inherently more uncertain that an approach based on stratification, although it is better able to show the effects of small changes in the influence.

In the example of traffic level above, changes in traffic levels (in the absence of compensating measures) make the ATCO busier, and so are related to the effect of ATCO resources, which has been quantified previously in IRP. Analysis of influences on separation incidents indicates that improved ATCO resources could have a maximum effect (ME) of a 45% reduction in ATCO errors (**Ref 1**), and it is assumed that reductions in traffic to the 5%ile level in the ACC distribution above would have approximately half this effect. Figure 3 shows the relationship between the traffic level and the modification factor.

Figure 3: Assumed Effect of Traffic Level on ATCO Errors



This allows the user to represent the airspace by entering a unit-specific value of the proxy metric, and the model can then calculate the corresponding MFs automatically. It is important to note that this relationship, and any unit-specific IRP results obtained from it, is critically dependent on the above assumptions[8]. Until the model can be validated, it must be considered extremely uncertain. As a rough indication, the uncertainty in the MFs is considered to range between 1 (i.e. no change from generic conditions) and MF^2.

In future work, it would be desirable to stratify the accident data by the selected proxy, in order to replace the assumptions with actual data. Meanwhile, it would be preferable to base the relationship between proxy and base events on structured expert judgement. The present analysis is considered to provide only a preliminary outline of the possible results from such a process.

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[8] Relationships of MFs to proxy values are assumed.

4.4 QUANTIFICATION OF STRATIFIED INFLUENCES

The key influence that is quantified through stratification is the airspace type, which is explained in Section 3. Several other stratified influences have previously been quantified in the CATS project (**Ref 9**), and these are adopted for the present work where relevant. However, this source does not provide a breakdown by airspace type or ACC, and this type of data would be desirable to improve the unit-specific model. The methodology for quantifying stratified influences is explained in (**Ref 1**).

4.5 QUANTIFICATION OF PERFORMANCE SCORES

The methodology for quantifying influences using performance scores is explained in (**Ref 1**). This is used in the unit-specific model for influences that are identified as important but which cannot be quantified in any other way.

4.6 SPECIFIC ASPECTS OF SAFETY MANAGEMENT SYSTEMS

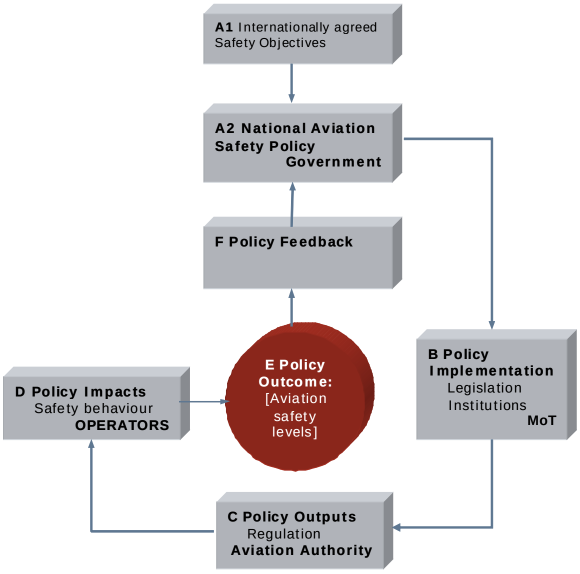
4.6.1 Aim

The aim of this section is to show within the IRP the effects of Safety Management System (SMS) performance on the ATM contribution to risk. Currently (baseline risk model), user inputs on safety management quality are used as a simple control on pilot and controller performance. The present section aims to improve the realism and utility of this modelling.

4.6.2 Safety Management

Safety management is a managerial process to control safety such that the required safety targets will be achieved and maintained. It exists at two levels. The first level at which safety management exists is at the level of a national state. At this level, aviation safety must be achieved through an effective and efficient public policy process (see **Figure 4**)

Figure 4: Aviation safety public policy process model (Ref 10)



The second level at which safety management exists is at the operational level of the different actors, i.e. within block D of Figure 4. The organisation of safety management at this level is through a Safety Management System. Because the IRP is primarily a description of the air transport at the operational level, the representation within IRP of the influence of safety management on accident risk should be done by representing the effects of Safety Management System performance on the ATM contribution to risk. The first level, the public policy level, will not be explicitly represented although the effect of the public policy level will be implicitly incorporated in the SMS performance.

4.6.3 Method

Although safety management is widely recognised as an important contributor to today's safety level, the exact influence of safety management on the actual level of safety is not known. Nevertheless, it is important to try to represent this influence in the IRP, if only to gain a better understanding of the relative safety priorities.

The simplest way to incorporate the effect of management in a risk model is by multiplying the probability of occurrence of the top event of the risk model by a factor which represents the overall quality of management. Initial research efforts therefore attempted to address safety management within a quantitative risk analysis by linking directly from the top event of a number of accident scenarios to the influences in the management system (**Ref 11**). Such a simplified approach gives little insight into the way in which management factors influence the risk number, and determining the 'quality of management' is a problem by itself. It is a reasonable approach when 'safety management' has a single common mode effect, whose management quality and its effects can be assessed (e.g. from audits) and which is fairly stable over time. In the aviation system however there are multiple (types of) organisations managing the different causal factors and events. A more sophisticated, and for the aviation system more appropriate, approach breaks down the quality of safety management into different common mode factors, where these factors can individually influence the probability of occurrence of the base events in the IRP. We therefore need to have a (comprehensive) model of safety management.

In most attempts to produce coherent and comprehensive models, safety management is represented as a control problem. The resulting models are based on control theory and contain feedback loops, see e.g. (**Ref 12**) to (**Ref 16**). Unfortunately, feed-back and feed-forward loops within safety management do not match with the tree structure of the IRP. Such a tree structure is not suited to include closed loops or dynamic information flows. For that reason, the process of safety management itself cannot be modelled, but only the resulting quality in terms of its influence on the individual events in the trees. The 'quality of safety management' is not directly observable or measurable and does not have a standard unit of measure unlike for instance length which is directly observable and measurable and has the meter as standard unit. Therefore criteria need to be developed that allow a distinction between levels of the quality of safety management. The quality of safety management is a multidimensional variable which much be split up into the different dimensions for quantification.

In (**Ref 17**), safety management is described as providing the necessary resources and criteria for safety critical tasks to be correctly executed. Generic delivery systems are defined to describe those resources and criteria. The following delivery systems related to human performance have been defined:

- *Competence*: The knowledge, skills and abilities in the form of first-line and/or back-up personnel who have been selected and trained for the safe execution of the critical tasks and activities in the organisation. This system covers the selection and training function of the company, which delivers sufficient competent staff for overall manpower planning. Competence should be seen as not only cognitive, but also physiological, i.e. it includes factors such as health and physiology (e.g. vision for pilots).
- *Availability*: Allocating the necessary time (or numbers) of competent people to the tasks which have to be carried out. This factor emphasises time-criticality, i.e. people available at the moment (or within the time frame) when the tasks must be carried

out. This delivery system is the responsibility of manpower planning. A critical aspect is planning for peak demands, particularly in emergency situations or other times when deviations from normal or planned operations occur.

- *Commitment*: The incentives and motivation which personnel have, in order to carry out their tasks and activities with suitable care and alertness, and according to the appropriate safety criteria and procedures specified by the organisation or by the workforce themselves for unexpected situations. This delivery system deals with the incentives of individuals carrying out the primary business activities not to choose other criteria above safety, such as ease of working, time saving, social approval, etc. The delivery system for this is often diffuse within companies, but includes many of the activities of supervision, social control, staff appraisal and incentive schemes.
- *Interface*: This covers the ergonomics of the interfaces which are used/operated by operations, inspection or maintenance. Included are both the appropriateness of the interface for the activity and the user-friendliness needed to carry out the activities.
- *Communication*: Communication refers to on-line communication necessary for risk control. It occurs implicitly or explicitly within any task activity when it involves more than one person. Proper communication ensures that the tasks are co-ordinated and everyone knows who is doing what. Communication and co-ordination is particularly critical within the cockpit (captain and first officer), between the aircraft and ATC and at maintenance shift changeovers or when an aircraft is handed over from operations to maintenance and back again.
- *Procedures*: Rules and procedures are specific performance criteria which specify in detail, often in written form, a formalised ‘normative’ behaviour or method for carrying out an activity. They may also cover informal ‘good practice’. They represent the ‘design’ of the human tasks.

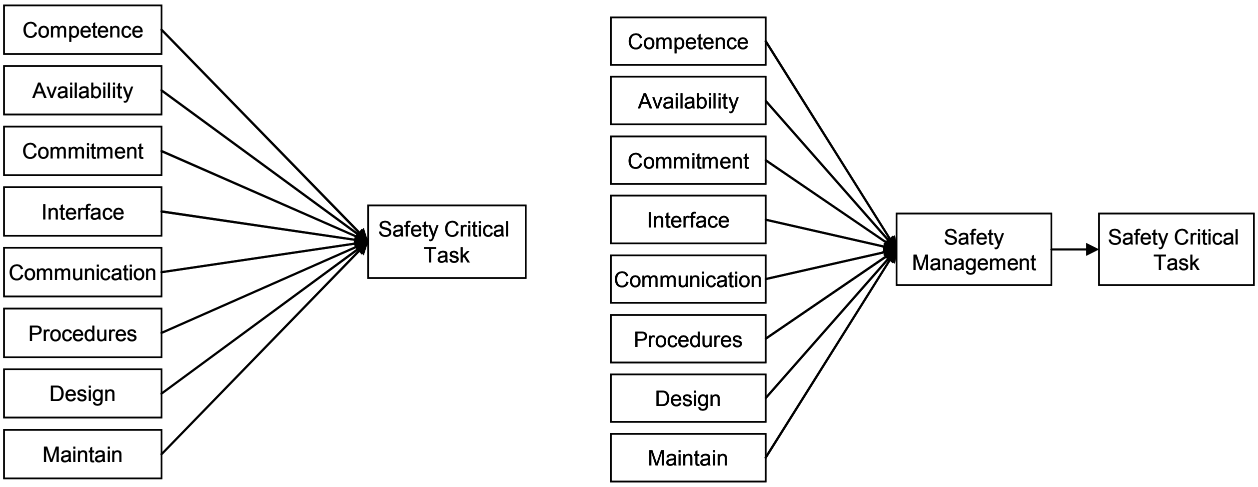
In addition to these human delivery systems, there are also technology delivery systems:

- *Design*: This delivery system deals with the process for ensuring that the hardware/ software risk control measures and risk control measure elements which have been specified are acquired or designed, either by purchase from outside, or by construction on site, are put in place and adjusted and that the spare parts or replacements purchased and stored for the maintenance phase of their life cycle are the correct ones and are in good condition when used.
- *Maintain*: This factor deals with the management processes for ensuring that the hardware/software risk control measures and risk control measure elements are kept in an effective state as specified by design or as modified to take account of improvements.

The delivery systems provide the means for quantification of the quality of safety management. Each delivery system is still very generic and can be specified further. To which detail this should go depends on the available efforts for modelling and the objectives to be reached. In CATS, proxy variables were selected to represent each of the delivery systems (**Ref 18**). For instance, the delivery system ‘competence’ of the flight crew was represented by the variables experience (the unit was total number of hours flown) and training (the unit was the number of days since the last type recurrent training).

The influence of safety management on safety critical tasks (base events in the IRP fault tree) can be represented for each of the individual delivery systems (shown left in Figure 5) or the influence can be represented for the aggregated quality of safety management (shown right in Figure 5).

Figure 5: Two options for representing the influence of safety management



Representing the influence for the aggregated quality of safety management has the advantage that the overall level of safety management as a function of the value of the delivery systems needs to be established only once. For each safety critical task there is then only one influence that needs to be determined. The disadvantage of this approach is that for some safety critical tasks the influence of for instance 'competence' may be stronger than for other safety critical tasks, but this cannot be represented. By representing the influence of each delivery system separately the individual influences on each safety critical task is represented but this has the drawback that for each safety critical task eight influences need to be determined. So while it allows a more detailed analysis and a better representation of reality it is also eight times more labour intensive to develop. Quantification of the influences must be done by structured expert judgement.

4.6.4 Progress

The approach for representing safety management in a quantitative risk model was initially developed in the CATS project and is still under development (**Ref 18**). Implementation into the IRP requires the following steps:

- Deciding on most appropriate option for representing the influence of safety management
- Identification of the fault tree base events that are influenced by safety management
- Specification of the delivery systems for each relevant base event
- Quantification of the influences by means of structured expert judgement

5 VERIFICATION

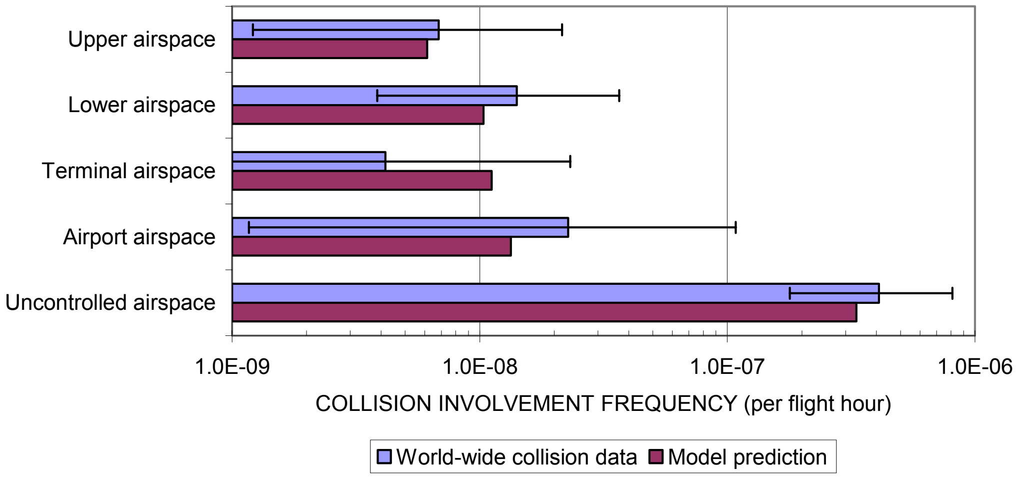
5.1 METHODOLOGY

The completed fault tree model is now verified against the overall data on accident frequencies in different airspaces. This is not an independent validation, since the same data was used as part of the model development. It cannot be an exact check, because many variations in the data have been neglected as not significant. However, it does confirm that the model has been constructed without obvious errors and that it gives a reasonable interpretation of the effects of airspace type on the accident risks.

5.2 MID-AIR COLLISION FREQUENCIES

Figure 6 compares the model predictions of mid-air collision frequency (MF5.3) with available accident data. Because there have been few mid-air collisions involving commercial aircraft, the breakdown of the frequency by airspace is very uncertain, as shown by the I-shaped bars in the figure. In each airspace type, the model prediction is within these uncertainty ranges[9]. This is considered to be acceptable verification.

Figure 6: Verification of Modelled Effect of Airspace on Mid-Air Collision Frequency



5.3 SEPARATION INCIDENT FREQUENCIES

Figure 7 compares the model predictions of risk ratio for separation incident frequency (MF_{MF5-8}) with the incident data used in the causal analysis. In each airspace type, the model prediction is within the uncertainty resulting from the small data quantity. This is considered to be acceptable verification.

It would be possible to improve the agreement for selected airspaces by further adjustment of model parameters, but this would violate the requirement that modelled effects should be physically meaningful. It is impossible to obtain exact agreement for all airspaces because of the constraint that the exposure-weighted average of each individual parameter must be 1 in the generic case.

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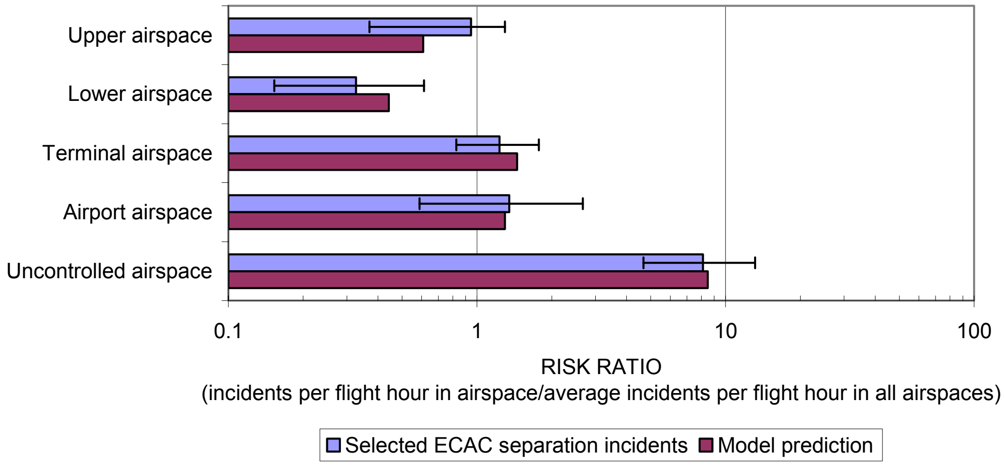
[9] The uncertainty bands are calculated in the same way as in (**Ref 1**).

Figure 7: Verification of Modelled Effect of Airspace on Separation Incident Frequency



5.4 PRECURSOR INCIDENT FREQUENCIES

Table 9 gives the model predictions of risk ratio for precursor MFs for each airspace type. It also obtains the overall average value by weighting each one by the generic flight exposure from Table 1.

These are not all exactly 1, because averaging the results of separate models is not the same as using a single model with averaged parameters. The difference is indicated by the average MFs, which range from 0.7 to 1.6. However, most are close to 1, and this is considered to be acceptable verification.

Table 9: Modelled Effect of Airspace on Precursor Events

EVENTS	Upper	Lower	Terminal	Airport	Uncon-trolled	Average
MF1 Fatal mid-air collision involvement	0.70	0.82	0.89	1.06	26.37	1.31
MF2 Fatal mid-air collision	0.66	0.87	0.84	1.50	31.98	1.44
MF3a Mid-air collision involvement	0.57	0.96	1.04	1.24	30.89	1.44
MF3 Mid-air collision	0.54	1.02	0.98	1.76	37.46	1.59
MF4 Imminent collision	0.56	0.49	1.36	2.28	14.20	1.10
MF5-8 Separation infringement	0.61	0.44	1.45	1.30	8.49	0.95
MF5 Separation infringement from plannable conflict	0.87	0.36	1.17	0.54	0.94	0.77
MF6 Separation infringement from unplannable conflict	0.51	0.72	2.08	1.78	0.18	1.00
MF7 Separation infringement from ATCO-induced conflict	1.41	0.09	1.40	0.45	1.23	0.96
MF8 Separation infringement from pilot-managed conflict	0.00	0.00	0.00	1.39	45.83	1.00
MF5.1 Plannable conflict	0.83	0.16	1.22	0.39	0.93	0.70
MF5.2 Pre-tactical conflict	1.05	0.17	1.30	0.41	0.03	0.79
MF5.3 Strategic conflict	0.70	0.33	2.51	0.80	0.01	1.00

EVENTS	Upper	Lower	Terminal	Airport	Uncon-trolled	Average
MF6.1 Unplannable conflict	0.62	0.74	1.98	1.38	0.03	1.00
MF6.1.1 Conflict due to airspace infringement	0.53	0.90	1.09	4.59	0.10	1.00
MF6.1.1.1 Airspace infringement by military aircraft	0.94	1.30	0.25	3.14	0.00	1.00
MF6.1.1.2 Airspace infringement by VFR aircraft	0.00	0.47	1.97	6.86	0.00	1.00
MF6.1.1.3 Airspace infringement by CAT aircraft	1.00	1.00	1.00	1.00	1.00	1.00
MF6.1.2 Conflict due to pilot deviation	0.66	0.67	2.34	0.07	0.00	1.00
MF6.1.2.1 Conflict due to level bust	0.63	0.65	2.45	0.00	0.00	1.00
MF6.1.2.2 Conflict due to lateral deviation	1.05	1.00	1.00	1.00	0.00	1.00
MF7.1 Trajectory instructions result in conflict	1.47	0.09	1.46	0.42	1.26	1.00
MF8.1 Pilot managed conflict	0.00	0.00	0.00	1.39	45.83	1.00
MB1 Ineffective visual warning	1.11	0.98	0.91	0.73	1.00	1.00
MB2 Ineffective ACAS warning	0.54	1.60	0.86	1.38	1.69	1.00
MB3 Ineffective STCA warning	0.84	1.05	0.95	1.76	1.68	1.00
MB4 Ineffective other ATCO warning	1.00	0.98	1.00	1.09	1.09	1.00
MB5 Ineffective management of plannable conflict	1.00	1.00	1.00	1.00	1.00	1.00
MB6 Ineffective management of unplannable conflict	1.00	1.00	1.00	1.00	1.00	1.00
MB7 Ineffective management of ATCO induced conflict	1.00	1.00	1.00	1.00	1.00	1.00
MB8 Ineffective conflict management by pilot	1.00	1.00	1.00	1.00	1.00	1.00
MB9 Ineffective sector planning	0.63	1.05	1.05	1.05	6.82	1.00
MC5 Ineffective procedural synchronisation	0.82	0.82	0.82	0.82	10.00	1.00
MB10 Ineffective DCB	1.50	0.52	0.52	0.52	5.00	1.00

5.5 UNIT-SPECIFIC INFLUENCES

The verifications above confirm the validity of the stratification of the fault tree model in Section 3. Separate validation of the unit-specific influences from Section 4 is not possible at present, because the model automatically delivers the generic average results (i.e. all MFi = 1) when the influences are set to the generic average values. It is possible to obtain distributions of model results, but at present there is no data against which these could be validated. In future work, it would be desirable to confirm face validity using expert judgement. This could be based on the results in the following section.

6 EXAMPLE RESULTS

6.1 EXAMPLE UNIT DEFINITIONS

To illustrate the results that are available from the unit-specific IRP, this section presents results for four example ATM units:

Generic en-route airspace. This is defined as between top-of-climb and top-of-descent, and covers only managed airspace. It represents an average of en-route airspace in the ECAC region.

Generic approach/departure airspace. This is defined as including (a) from end of initial climb to top-of-climb, and (b) from top-of-descent to start of final approach. It represents an average of approach/departure airspace in the ECAC region.

Generic airport. This is defined as including initial climb, final approach, runway operations and other movements on the airport surface. It represents an average of airport airspace and airport surfaces in the ECAC region.

An area control centre (ACC) managing en-route airspace in an example ECAC country. It represents an average of sectors and flight movements within the specific ACC.

For the various examples, the inputs are different but the same model is used for all cases. Cases 1 to 3 are apportionment of the ECAC-wide generic model. Case 4 is a specific operational unit.

At present the example results are for the 2005 baseline (representing current operations). Once the SESAR operational improvements are fully defined, IRP will be able to deliver results corresponding to any time period between 2005 and 2020.

6.2 GENERIC EN-ROUTE AIRSPACE

6.2.1 Definition

The en-route phase is defined as between top-of-climb and top-of-descent. This is identical to the cruise phase defined in Section 2.4.6. The duration is estimated as 51 minutes (i.e. 0.85 hours) per flight, or 57% of an average flight.

The corresponding airspace distribution is obtained from the joint distribution in Table 3 with the results shown in Table 10. This unit covers only managed airspace, but this is already reflected in the distribution. The table can be interpreted as showing that for 70% of flights (mainly jets) the cruise phase is in upper airspace, while for 30% of flights (mainly turboprops, but also short flights with jets) the cruise phase is in lower airspace.

Table 10: Airspace Type Distribution for En-Route Airspace

AIRSPACE TYPE	EXPOSURE (% of flight time)
Upper airspace	70%
Lower airspace	30%
Terminal airspace	0%
Airport airspace	0%
Uncontrolled airspace	0%
Temporary airspace	0%
TOTAL	100%

For simplicity, all other inputs are set to their generic values in this case.

6.2.2 Fatal Accident Frequencies

Table 11 shows the overall results for this case in the form of frequencies of fatal accidents of the 5 categories that are modelled in IRP. Mid-air collision is the main contributor for this case.

Table 11: Fatal Accident Frequencies for En-Route Airspace

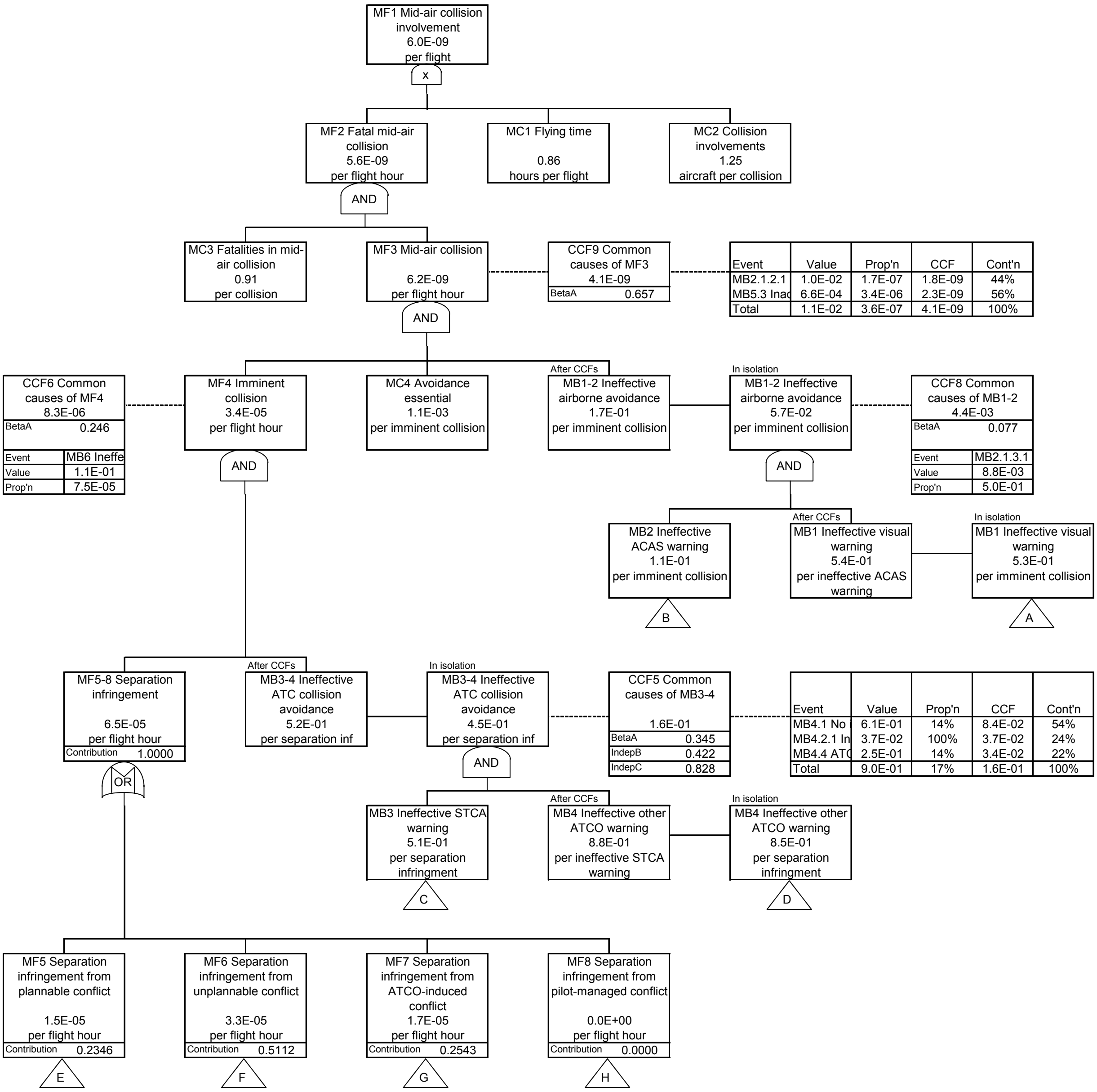
ACCIDENT CATEGORY	FREQUENCY (per flight)	% OF TOTAL	FRACTION OF BASE CASE
Mid-air collision	6.0E-09	78%	0.455
Runway collision	0.0E+00	0%	0.000
Taxiway collision	0.0E+00	0%	0.000
CFIT	1.1E-09	15%	0.021
Wake turbulence accident	5.2E-10	7%	0.163
Total ATM influenced accidents	7.6E-09	100%	0.082

The last column of the table shows the results expressed as a fraction of the corresponding frequencies in the base case for all ECAC airspace. The frequency of mid-air collision is approximately 46% of the ECAC total, and this is explained further below. The frequencies of CFIT and wake turbulence accidents are respectively 2% and 16% of the ECAC total, and simply reflect the proportions of these accidents that occur in the cruise flight phase in the accident/incident data on which IRP is based (Table 7).

6.2.3 Mid-Air Collision Risks

Figure 8 shows the top levels of the mid-air collision fault tree, as obtained by IRP for en-route airspace. This is the first form of results provided by IRP for mid-air collisions, from which the other results are derived. The main structure is explained in detail in the methodological part of (**Ref 1**). The results shown here incorporate the unit-specific modifications for this case, as explained in Section 3. The top event frequency for fatal mid-air collision involvements of 6.0 x 10-9 per flight is the result shown in Table 11.

Figure 8: Mid-Air Collision Fault Tree for En-Route Airspace



Event	Value	Prop'n	CCF	Cont'n
MB2.1.2.1	1.0E-02	1.7E-07	1.8E-09	44%
MB5.3 Inac	6.6E-04	3.4E-06	2.3E-09	56%
Total	1.1E-02	3.6E-07	4.1E-09	100%

Event	Value	Prop'n	CCF	Cont'n
MB4.1 No i	6.1E-01	14%	8.4E-02	54%
MB4.2.1 In	3.7E-02	100%	3.7E-02	24%
MB4.4 ATC	2.5E-01	14%	3.4E-02	22%
Total	9.0E-01	17%	1.6E-01	100%

Figure 9 shows an alternative presentation of this type of information, in the form of a barrier diagram10. This shows the main precursor event frequencies and the main barrier failure probabilities. For simplicity, it shows only the barrier failure probabilities after the effects of common-cause failures (CCFs). This produces some minor differences in barrier failure probabilities compared to Figure 8. The accident frequency for mid-air collisions of 6.2 x 10-9 per flight hour is for event MF3, and appears on the third row of Figure 8.

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[10] Although the current results are for the 2005 baseline, the barrier model uses SESAR 'terminology' (e.g. SBT, RBT). We agree it would be better to use current terminology, but the results are taken direct from IRP tool, which at present does not have a facility to change terminology according to the input date. Equivalence of SESAR and current terminology is explained in (**Ref 1**).

Figure 9: Barrier Model of Mid-Air Collision for En-Route Airspace

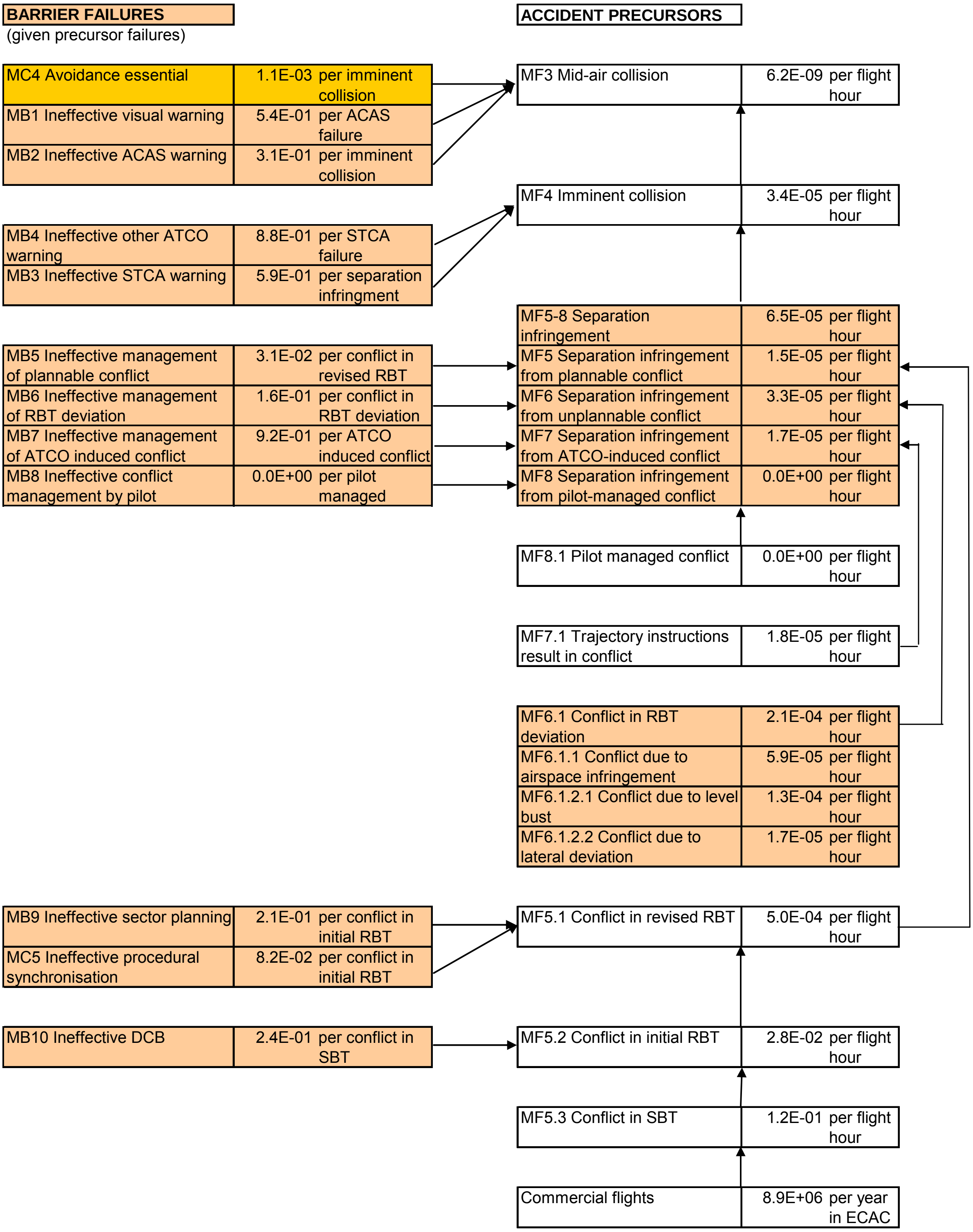


Table 12 shows the frequencies of precursors and probabilities of barrier failures expressed as fractions of the corresponding values in the base case for all ECAC airspace. In most cases, these are a combination of the values from Table 9, weighted as in Table 10 (although MF1 is an exception because it is also affected by flight time).

Table 12: Mid-Air Collision Precursors for En-Route Airspace

EVENT	PROBABILITY	UNITS	FRACTION OF BASE
MF1 Fatal mid-air collision involvement	6.0E-09	per flight	0.455
MF2 Fatal mid-air collision	5.6E-09	per flight hour	0.778
MF3a Mid-air collision involvement	7.7E-09	per flight hour	0.718
MF3 Mid-air collision	6.2E-09	per flight hour	0.701
MF4 Imminent collision	3.4E-05	per flight hour	0.544
MF5-8 Separation infringement	6.5E-05	per flight hour	0.558
MF5 Separation infringement from plannable conflict	1.5E-05	per flight hour	0.692
MF6 Separation infringement from unplannable conflict	3.3E-05	per flight hour	0.571
MF7 Separation infringement from ATCO-induced conflict	1.7E-05	per flight hour	1.050
MF8 Separation infringement from pilot-managed conflict	0.0E+00	per flight hour	0.000
MF5.1 Plannable conflict	5.0E-04	per flight hour	0.594
MF5.2 Pre-tactical conflict	2.8E-02	per flight hour	0.710
MF5.3 Strategic conflict	1.2E-01	per flight hour	0.589
MF6.1 Unplannable conflict	2.1E-04	per flight hour	0.655
MF6.1.1 Conflict due to airspace infringement	5.9E-05	per CAT flight hour	0.639
MF6.1.1.1 Airspace infringement by military aircraft	6.2E-05	per CAT flight hour	1.050
MF6.1.1.2 Airspace infringement by VFR aircraft	8.1E-06	per CAT flight hour	0.139
MF6.1.1.3 Airspace infringement by CAT aircraft	1.3E-05	per CAT flight hour	1.000
MF6.1.2 Conflict due to pilot deviation	1.5E-04	per flight hour	0.661
MF6.1.2.1 Conflict due to level bust	1.3E-04	per flight hour	0.631
MF6.1.2.2 Conflict due to lateral deviation	1.7E-05	per flight hour	1.035
MF7.1 Trajectory instructions result in conflict	1.8E-05	per flight hour	1.058
MF8.1 Pilot managed conflict	0.0E+00	per flight hour	0.000
MB1 Ineffective visual warning	5.3E-01	per imminent collision	1.070
MB2 Ineffective ACAS warning	1.1E-01	per imminent collision	0.861
MB3 Ineffective STCA warning	5.1E-01	per separation inf	0.904
MB4 Ineffective other ATCO warning	8.5E-01	per separation inf	0.993
MB5 Ineffective management of plannable conflict	2.0E-02	per plannable conflict	1.000
MB6 Ineffective management of unplannable conflict	1.1E-01	per unplannable conflict	1.000
MB7 Ineffective management of ATCO induced conflict	8.0E-01	per ATCO induced conflict	1.000
MB8 Ineffective conflict management by pilot	1.0E-01	per pilot managed conflict	1.000

EVENT	PROBABILITY	UNITS	FRACTION OF BASE
MB9 Ineffective sector planning	7.0E-02	per pre-tactical conflict	0.758
MC5 Ineffective procedural synchronisation	8.2E-02	per pre-tactical conflict	0.816
MB10 Ineffective DCB	2.4E-01	per strategic conflict	1.207

This table may be interpreted as follows. Event MF1 shows that, as above, the overall number of fatal accidents per flight in en-route airspace is 46% of the ECAC total. The time spent in the airspace is 57% of the total (Section 6.2.1), so the frequency of fatal accidents *per flight-hour* in en-route airspace is 78% of the ECAC average. Event MF2 also takes account of small changes in the probability of two commercial aircraft being involved in the collision in en-route airspace. Event MF3 takes account of the probability of fatalities, which is slightly higher in en-route airspace. Event MF4 takes account of changes in the probability of visual and ACAS warning failure (MB1 and MB2), which combine performance in upper and lower airspace and result in better than average performance overall, mainly due to more extensive ACAS fitment, which results from the lower than average proportion of VFR traffic. The whole table may be interpreted in the same way, with the aid of the mid-air collision fault tree. Values of 1.000 in the table indicate that no deviation from the average probability is modelled for that event.

The largest change is that pilot-managed conflicts (MF8) become zero, because at present they do not occur in controlled airspace. The next largest change arises from the fact that most VFR infringements occur in terminal and airport airspace, so the frequency in en-route airspace is calculated as 14% of the ECAC total (MF6.1.1.2).

Another important change arises from the fact that most strategic conflicts occur in terminal airspace, so the frequency in en-route airspace is calculated as 59% of the ECAC total (MF5.3). Combined with a worse than average performance of DCB (MB10), which is considered to be most effective in terminal airspace, this indicates that pre-tactical conflicts in en-route airspace will have a frequency 71% of the total (MF5.2). The much better than average performance of sector planning (MB9) and procedural synchronisation (MC5) are slightly offset by the common cause modelling, but nevertheless indicate that plannable conflicts in en-route airspace will have a frequency 59% of the total (MF5.1).

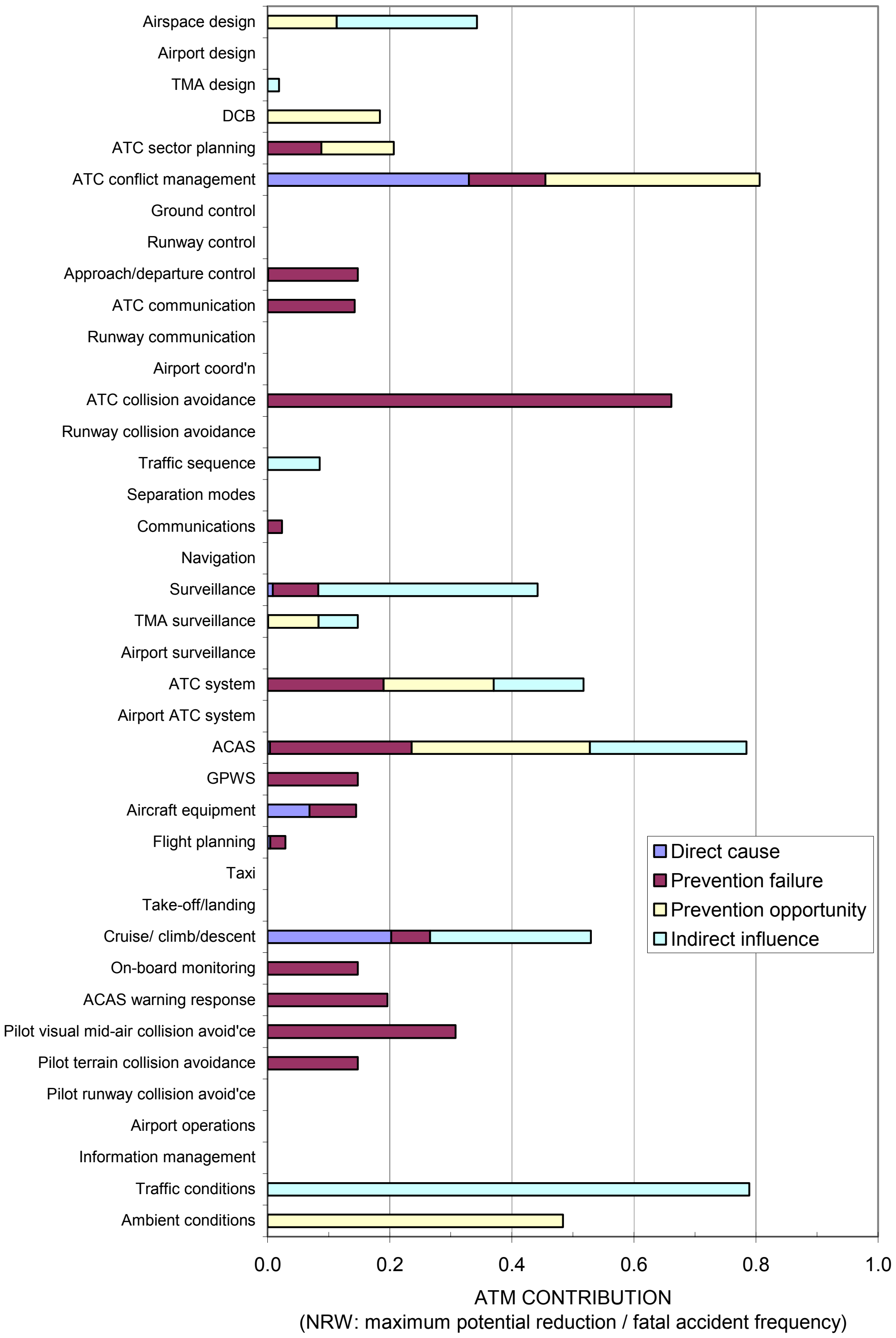
The above results are sensitive to the definition of en-route airspace as the combination of upper and lower airspace. If only upper airspace was used, the results would be as in Table 9. It is emphasised that these results are preliminary estimates, which have not yet been validated through expert scrutiny. It is possible that substantial changes may occur when individual factors are examined in detail. Nevertheless, they are sufficient to indicate the type of results that are available, and the level of traceability that is possible through the fault tree model. In addition to the results presented above, all IRP results (i.e. fault trees, influence models, positive and negative contributions etc) are available for each case. These are not presented here because the relative changes above are easier to interpret.

6.2.4 ATM Contributions

Figure 10 shows the risk picture as obtained by IRP for en-route airspace in the form of ATM contributions to the overall fatal accident frequency. This includes contributions to all accident categories (not just mid-air collisions), in the proportions shown in Table 11. The contributions are expressed as non-dimensional risk reduction worth (NRW), equal to the maximum potential reduction in accident frequency per flight if the ATM elements could somehow stop causing accidents or adversely influencing their probability, divided by the overall ATM influenced fatal accident frequency of 7.6×10^{-9} per flight. These are the negative contributions of ATM to accident risks, which could be reduced by ATM improvements.

The largest contribution is from ATC conflict management. This has a large direct contribution to mid-air collisions, due to errors that induce conflicts (MB7) or misjudgement of plannable conflicts (MB5.1). It can also fail to prevent conflicts by failure to identify unplannable conflicts in time (MB6.1.2). Hence, improvements in ATCO reliability have the potential to make significant risk reductions. In principle, there is a prevention opportunity if independent monitoring can be extended (MB4.1).

Figure 10: ATM Contributions to Risks in En-Route Airspace



ACAS is the element with the second largest contribution. A significant proportion of aircraft (e.g. military, VFR) do not have ACAS fitted (MB2.1.1). ACAS logic failures, although rare, may be common causes of failure of this barrier on both aircraft (MB2.1.2.2). Given high coverage of ACAS on commercial aircraft in upper airspace, and the reliability of response by flight crew, the contribution of these common causes becomes more important than average.

ATC collision avoidance also makes a large contribution to mid-air collisions, due to failure to respond to STCA in time (MB3.3, MB3.4) and warning from other ATCOs (MB4.3, MB4.4). In cases such as en-route airspace, where STCA coverage and reliability are high, these human responses to the warning become more important than average.

Traffic conditions have a large indirect influence, as may be obvious. The collision risks per flight are directly proportional to the overall traffic level (not shown in Figure 10 for clarity). The detailed risk picture indicates that traffic complexity is the largest influence on collision risk.

ATM elements that affect other accident categories make relatively small contributions in these results.

6.3 GENERIC APPROACH/DEPARTURE AIRSPACE

6.3.1 Definition

The approach/departure phase is defined as including (a) from end of initial climb to top-of-climb, and (b) from top-of-descent to start of final approach. This includes the phases climb to cruise, descent, holding, initial approach, intermediate approach and missed approach from Section 2.4. The average duration of these phases is estimated as 33 minutes (i.e. 0.55 hours) per flight.

The corresponding airspace distribution is obtained from the joint distribution in Table 3. This unit covers only managed airspace, so the uncontrolled airspace component is eliminated from the distribution. The results are shown in Table 13. This table can be interpreted as showing that for 66% of flights (mainly at large airports) the approach/departure is in a TMA, while for 34% of flights (mainly at small airports) the approach/departure is in lower airspace.

Table 13: Airspace Type Distribution for Approach/Departure Airspace

AIRSPACE TYPE	EXPOSURE (% of flight time)
Upper airspace	0%
Lower airspace	34%
Terminal airspace	66%
Airport airspace	0%
Uncontrolled airspace	0%
Temporary airspace	0%
TOTAL	100%

For simplicity, all other inputs are set to their generic values in this case.

6.3.2 Fatal Accident Frequencies

Table 14 shows the overall results for this case in the form of frequencies of fatal accidents of the 5 categories that are modelled in IRP. It shows that CFIT dominates these results.

Table 14: Fatal Accident Frequencies for Approach/Departure Airspace

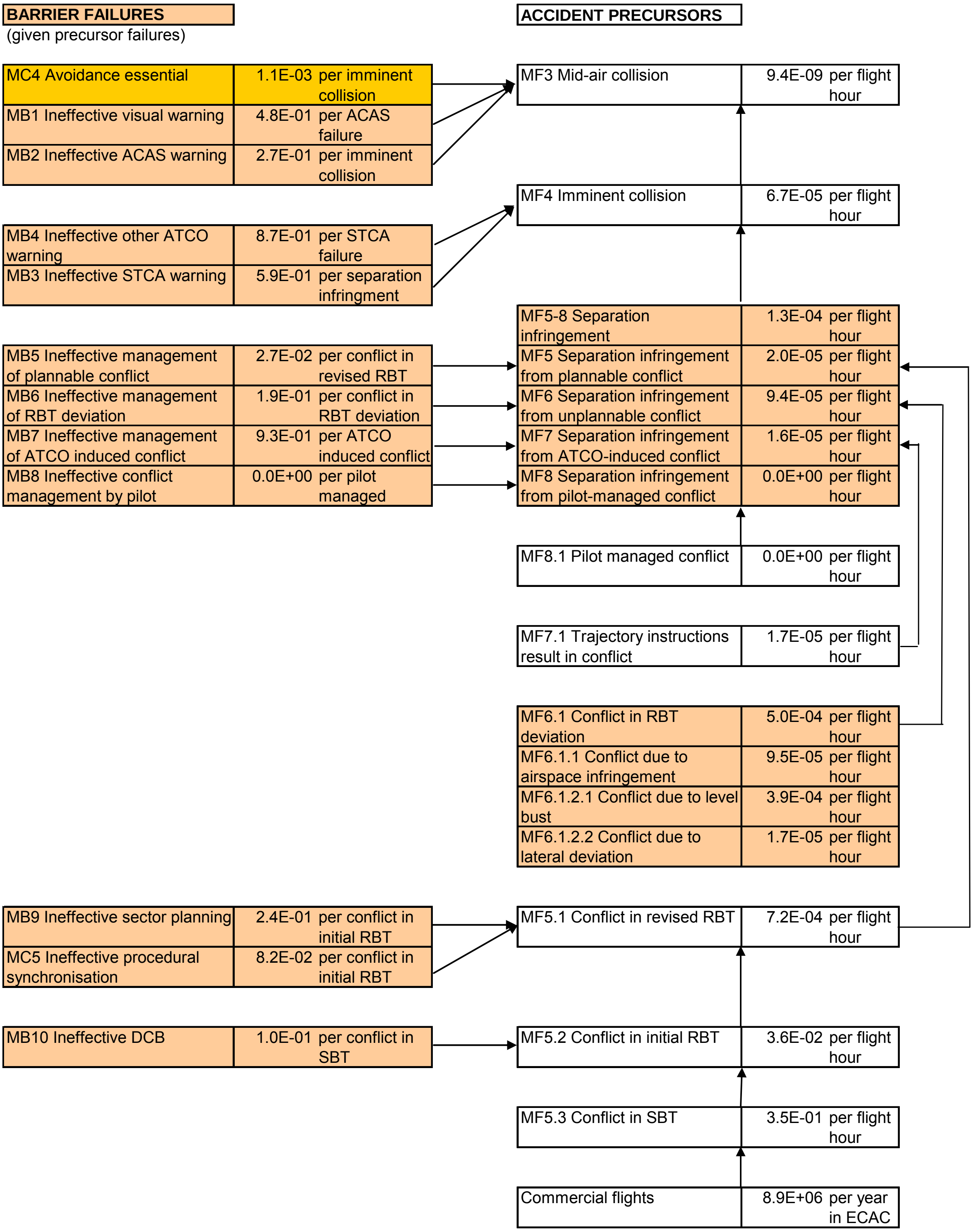
ACCIDENT CATEGORY	FREQUENCY (per flight)	% OF TOTAL	FRACTION OF BASE CASE
Mid-air collision	4.5E-09	14%	0.344
Runway collision	0.0E+00	0%	0.000
Taxiway collision	0.0E+00	0%	0.000
CFIT	2.7E-08	83%	0.502
Wake turbulence accident	8.6E-10	3%	0.268
Total ATM influenced accidents	3.3E-08	100%	0.350

The last column of the table shows the results expressed as a fraction of the corresponding frequencies in the base case for all ECAC airspace. The frequency of mid-air collision is 34% of the ECAC total, and this is explained further below. The frequencies of CFIT and wake turbulence accidents are respectively 50 and 27% of the ECAC total, and simply reflect the proportions of these accidents that occur in the selected flight phases in the accident data on which IRP is based.

6.3.3 Mid-Air Collision Risks

Figure 11 shows the mid-air collision risks in this case as a barrier diagram. The frequencies per flight hour are averages per hour spent in the defined airspace, and thus cannot be added directly to the values in Section 6.2.

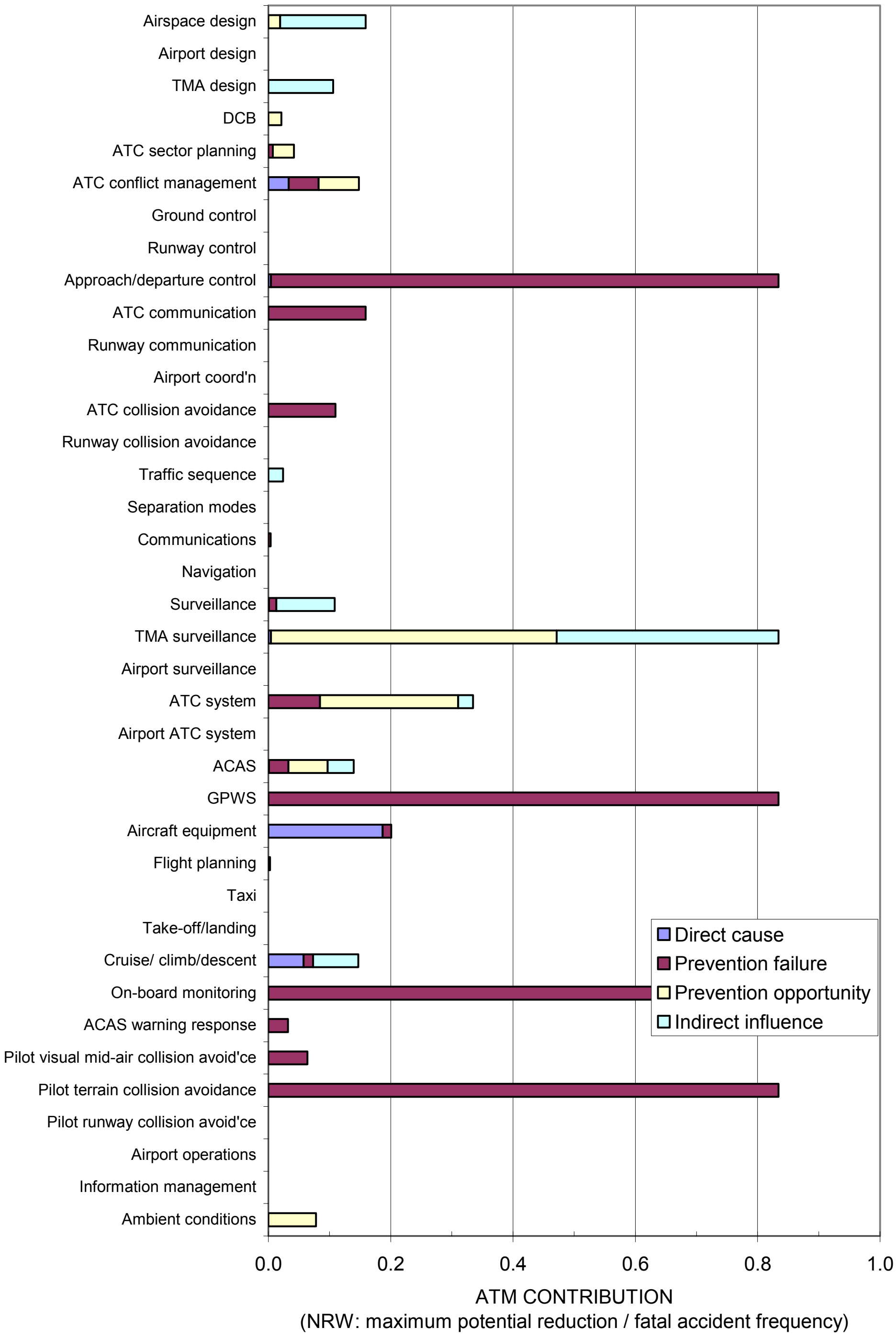
Figure 11: Barrier Model of Mid-Air Collision for Approach/Departure Airspace



6.3.4 ATM Contributions

Figure 12 shows the risk picture in the form of ATM contributions to the fatal accident frequencies in Table 14.

Figure 12: ATM Contributions to Risks in Approach/Departure Airspace



The largest contributions are from the barriers relevant to CFIT risks, since CFIT dominates the results in Table 14. These barriers include on-board monitoring, GPWS and pilot terrain avoidance. These are counted as ATM influences because ATM is defined according to the function being carried out (in this case terrain separation), rather than by the organisation carrying it out. The more obviously ATM contributions are approach/departure control (since the controller has the intention of preventing CFIT by giving terrain avoidance warning) and TMA surveillance (mainly an opportunity, since terrain area radar is often not available in mountainous areas where CFIT risk is high).

6.4 GENERIC AIRPORT

6.4.1 Definition

The airport phase is defined as including the phases take off, initial climb, final approach and landing from Section 2.4, together with runway operations and other movements on the airport surface. The average duration of these phases is estimated as 8 minutes (i.e. 0.14 hours) in flight per flight plus 15 minutes on the ground. The corresponding airspace distribution is 100% in airport airspace.

For simplicity, all other inputs are set to their generic values in this case.

6.4.2 Fatal Accident Frequencies

Table 15 shows the overall results for this case in the form of frequencies of fatal accidents of the 5 categories that are modelled in IRP. It also shows the results expressed as a fraction of the corresponding frequencies in the base case for all ECAC airspace.

Table 15: Fatal Accident Frequencies for Airport

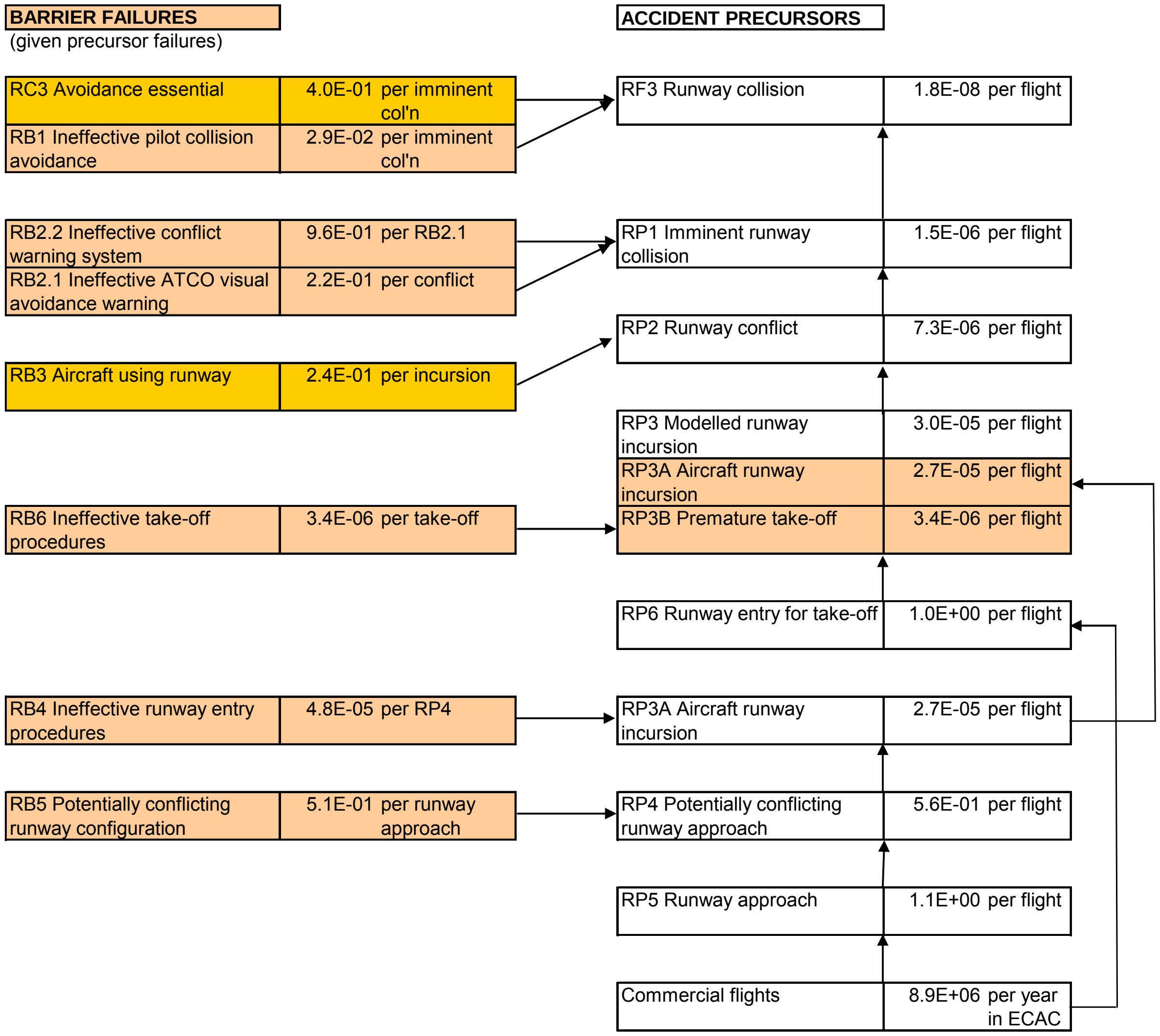
ACCIDENT CATEGORY	FREQUENCY (per flight)	% OF TOTAL	FRACTION OF BASE CASE
Mid-air collision	8.4E-10	2%	0.064
Runway collision	2.2E-08	43%	1.000
Taxiway collision	5.5E-10	1%	1.000
CFIT	2.6E-08	51%	0.481
Wake turbulence accident	1.8E-09	4%	0.569
Total ATM influenced accidents	5.1E-08	100%	0.551

The frequency of mid-air collision is 6% of the ECAC total, and the risk picture follows the same modifications shown for airport airspace in Table 9. The frequencies of CFIT and wake turbulence accidents are respectively 48 and 57% of the ECAC total, and simply reflect the proportions of these accidents that occur in the selected flight phases in the accident data on which IRP is based. The frequencies of runway and taxiway collisions are 100% of ECAC total by definition.

6.4.3 Runway Collision Risks

Figure 13 shows the runway collision risks in this case as a barrier diagram.

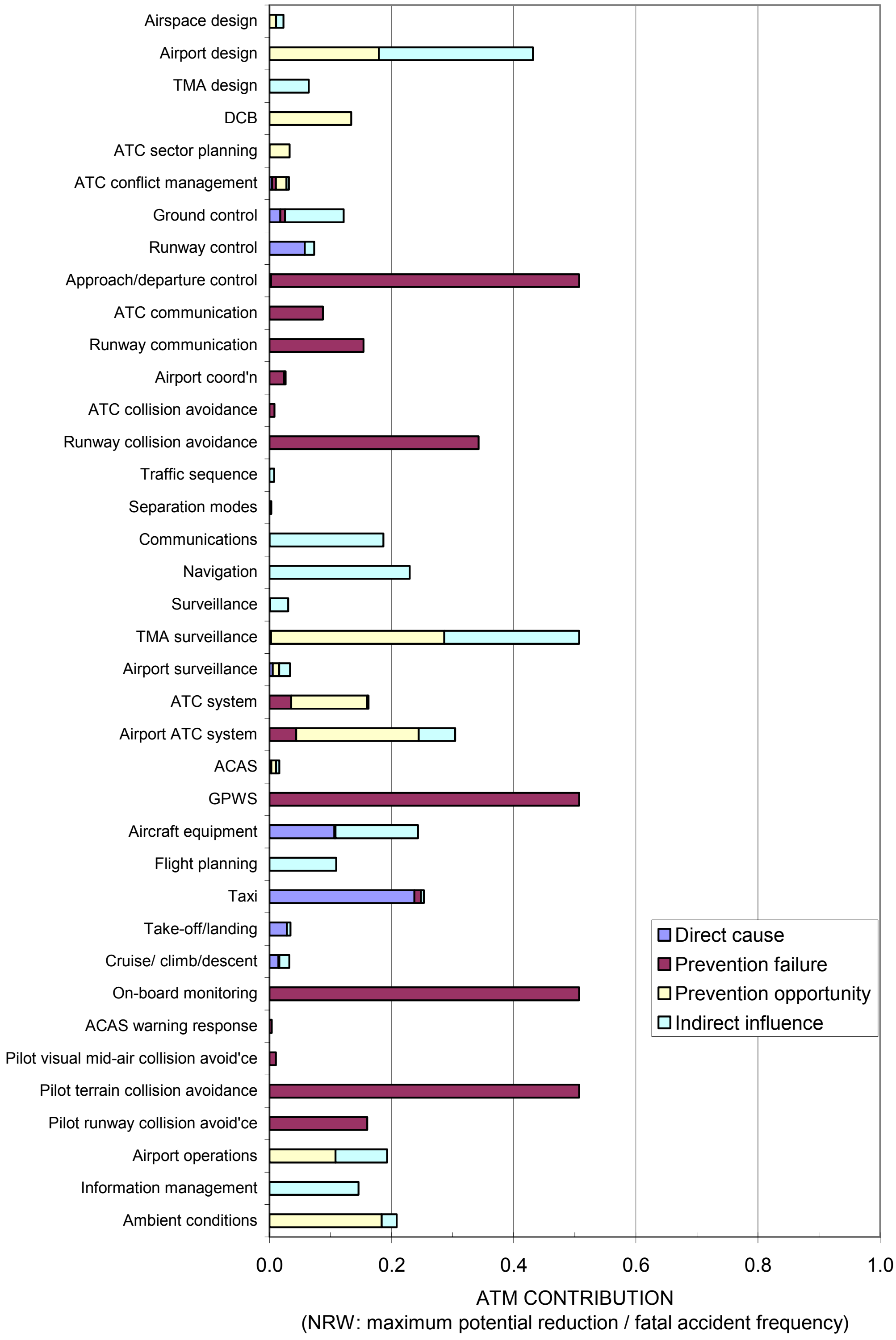
Figure 13: Barrier Model of Runway Collision for Airport



6.4.4 ATM Contributions

Figure 14 shows the risk picture in the form of ATM contributions to the fatal accident frequencies in Table 15. Because of the results above, this is roughly an average of the corresponding pictures for CFIT and runway collision.

Figure 14: ATM Negative Contributions to Risks in Airport


Airspace design
Airport design
TMA design
DCB
ATC sector planning
ATC conflict management
Ground control
Runway control
Approach/departure control
ATC communication
Runway communication
Airport coord'n
ATC collision avoidance
Runway collision avoidance
Traffic sequence
Separation modes
Communications
Navigation
Surveillance
TMA surveillance
Airport surveillance
ATC system
Airport ATC system
ACAS
GPWS
Aircraft equipment
Flight planning
Taxi
Take-off/landing
Cruise/ climb/descent
On-board monitoring
ACAS warning response
Pilot visual mid-air collision avoid'ce
Pilot terrain collision avoidance
Pilot runway collision avoid'ce
Airport operations
Information management
Ambient conditions
Direct cause
Prevention failure
Prevention opportunity
Indirect influence
0.0
0.2
0.4
0.6
0.8
1.0
ATM CONTRIBUTION
(NRW: maximum potential reduction / fatal accident frequency)

6.5 EN-ROUTE ACC

6.5.1 Definition

The en-route ACC in an example ECAC country has the following exposure parameters:

- 1.952 million IFR movements per year
- 532,000 controlled flight hours
- 4.55% of ECAC controlled flight hours
- 16 minutes (0.27 hours) average transit time

Table 16 shows the estimated airspace distribution, based on the distribution of flight levels. This shows that this ACC is more weighted towards upper airspace than the generic en-route airspace above, but still includes a significant fraction of lower airspace.

Table 16: Airspace Type Distribution for Example En-Route ACC

AIRSPACE TYPE	EXPOSURE (% of flight time)
Upper airspace	86%
Lower airspace	14%
Terminal airspace	0%
Airport airspace	0%
Uncontrolled airspace	0%
Temporary airspace	0%
TOTAL	100%

Table 17 shows the estimated flight phase distribution, which is obtained from the joint distribution of flight phase and airspace type (Table 3). The flight lengths of each phase have been adjusted in proportion to match the average transit time above.

Table 17: Flight Phase Distribution for Example En-Route ACC

FLIGHT PHASE	EXPOSURE (% of flight time)	EXPOSURE (hours per flight)	EXPOSURE MODIFICATION FACTOR
Taxi	0.0%	0.000	0.000
Take-off	0.0%	0.000	0.000
Initial climb	0.0%	0.000	0.000
Climb to cruise	2.3%	0.006	0.030
Cruise	94.1%	0.257	0.300
Descent	1.7%	0.005	0.028
Holding	0.0%	0.000	0.000
Initial approach	1.8%	0.005	0.038
Intermediate approach	0.0%	0.000	0.000
Final approach	0.0%	0.000	0.000
Landing	0.0%	0.000	0.000

FLIGHT PHASE	EXPOSURE (% of flight time)	EXPOSURE (hours per flight)	EXPOSURE MODIFICATION FACTOR
Missed approach	0.0%	0.000	0.028
Manoeuvring	0.1%	0.000	0.182
TOTAL (excluding taxi)	100.0%	0.273	0.182

The table includes the exposure modification factor (EMF) for each flight phase, as defined in Section 3.4. This shows that the chosen ACC includes 30% of a typical cruise phase, and smaller proportions of the other flight phases, totalling the 16 minute average transit time above.

Table 18 shows the other influence metrics for this ACC, both as absolute values and as relative levels divided by ECAC average. This shows that the ACC is large (i.e. with a low handover score), with a high level of traffic saturation, and a high degree of compliance with safety management requirements.

Table 18: Influence Metrics for Example En-Route ACC

METRIC	VALUE	ECAC AVERAGE	RELATIVE LEVEL
Traffic level (aircraft per sector)	3.78	2.92	1.297
Traffic complexity (aggregated complexity score)	8.10	5.90	1.373
Traffic saturation (ATFM en route delay min/flight)	2.25	1.37	1.647
Traffic variability (peak /average traffic)	1.14	1.22	0.938
Handover score (% of handovers outside ACC)	4%	10%	0.410
Compliance score (% of harmonisation objectives completed)	82%	53%	1.553
% conflicts covered by STCA	100%	78%	1.278

For simplicity, all other inputs are set to their generic values in this case.

6.5.2 Fatal Accident Frequencies

Table 19 shows the overall results for this case in the form of frequencies of fatal accidents of the 5 categories that are modelled in IRP. It also shows the results expressed as a fraction of the corresponding frequencies in the base case for all ECAC airspace.

Table 19: Fatal Accident Frequencies for En-Route ACC

ACCIDENT CATEGORY	FREQUENCY (per flight)	% OF TOTAL	FRACTION OF BASE CASE
Mid-air collision	2.4E-09	32%	0.183
Runway collision	0.0E+00	0%	0.000
Taxiway collision	0.0E+00	0%	0.000
CFIT	4.0E-09	53%	0.075
Wake turbulence accident	1.2E-09	15%	0.360
Total ATM influenced accidents	7.6E-09	100%	0.082

The frequency of mid-air collision is approximately 18% of the ECAC average, and this is explained further below. The frequencies of CFIT and wake turbulence accidents are respectively 8% and 36% of the ECAC average, and simply reflect the proportions of these accidents that occur in the cruise flight phase in the accident data on which IRP is based.

6.5.3 Mid-Air Collision Risks

Table 20 shows the frequencies of precursors and probabilities of barrier failures for mid-air collision. In most cases, these are a combination of the values from Table 9, weighted as in Table 10 (although MF1 is an exception because it is also affected by flight time).

Table 20: Mid-Air Collision Precursors for En-Route ACC

EVENT	FREQUENCY	UNITS	FRACTION OF BASE
MF1 Fatal mid-air collision involvement	2.4E-09	per flight	0.183
MF2 Fatal mid-air collision	6.6E-09	per flight hour	0.919
MF3a Mid-air collision involvement	8.8E-09	per flight hour	0.821
MF3 Mid-air collision	6.9E-09	per flight hour	0.787
MF4 Imminent collision	4.6E-05	per flight hour	0.735
MF5-8 Separation infringement	9.1E-05	per flight hour	0.781
MF5 Separation infringement from plannable conflict	2.3E-05	per flight hour	1.052
MF6 Separation infringement from unplannable conflict	4.2E-05	per flight hour	0.721
MF7 Separation infringement from ATCO-induced conflict	2.6E-05	per flight hour	1.638
MF8 Separation infringement from pilot-managed conflict	0.0E+00	per flight hour	0.000
MF5.1 Plannable conflict	7.8E-04	per flight hour	0.930
MF5.2 Pre-tactical conflict	4.6E-02	per flight hour	1.140
MF5.3 Strategic conflict	1.7E-01	per flight hour	0.838
MF6.1 Unplannable conflict	2.7E-04	per flight hour	0.834
MF6.1.1 Conflict due to airspace infringement	7.0E-05	per CAT flight hour	0.754
MF6.1.1.1 Airspace infringement by military aircraft	5.9E-05	per CAT flight hour	0.994
MF6.1.1.2 Airspace infringement by VFR aircraft	3.8E-06	per CAT flight hour	0.066
MF6.1.1.3 Airspace infringement by CAT aircraft	1.3E-05	per CAT flight hour	1.000
MF6.1.2 Conflict due to pilot deviation	2.0E-04	per flight hour	0.867
MF6.1.2.1 Conflict due to level bust	1.7E-04	per flight hour	0.828
MF6.1.2.2 Conflict due to lateral deviation	2.3E-05	per flight hour	1.356
MF7.1 Trajectory instructions result in conflict	2.8E-05	per flight hour	1.653
MF8.1 Pilot managed conflict	0.0E+00	per flight hour	0.000
MB1 Ineffective visual warning	5.4E-01	per imminent collision	1.090
MB2 Ineffective ACAS warning	8.5E-02	per imminent collision	0.693
MB3 Ineffective STCA warning	4.8E-01	per separation inf	0.855

EVENT	FREQUENCY	UNITS	FRACTION OF BASE
MB4 Ineffective other ATCO warning	8.7E-01	per separation inf	1.016
MB5 Ineffective management of plannable conflict	2.1E-02	per plannable conflict	1.033
MB6 Ineffective management of unplannable conflict	1.2E-01	per unplannable conflict	1.030
MB7 Ineffective management of ATCO induced conflict	8.3E-01	per ATCO induced conflict	1.037
MB8 Ineffective conflict management by pilot	1.0E-01	per pilot managed conflict	1.029
MB9 Ineffective sector planning	6.5E-02	per pre-tactical conflict	0.703
MC5 Ineffective procedural synchronisation	8.2E-02	per pre-tactical conflict	0.816
MB10 Ineffective DCB	2.7E-01	per strategic conflict	1.361

Figure 15shows the runway collision risks in this case as a barrier diagram.

Figure 15: Barrier Model for Barrier Model of Mid-Air Collision for En-Route ACC

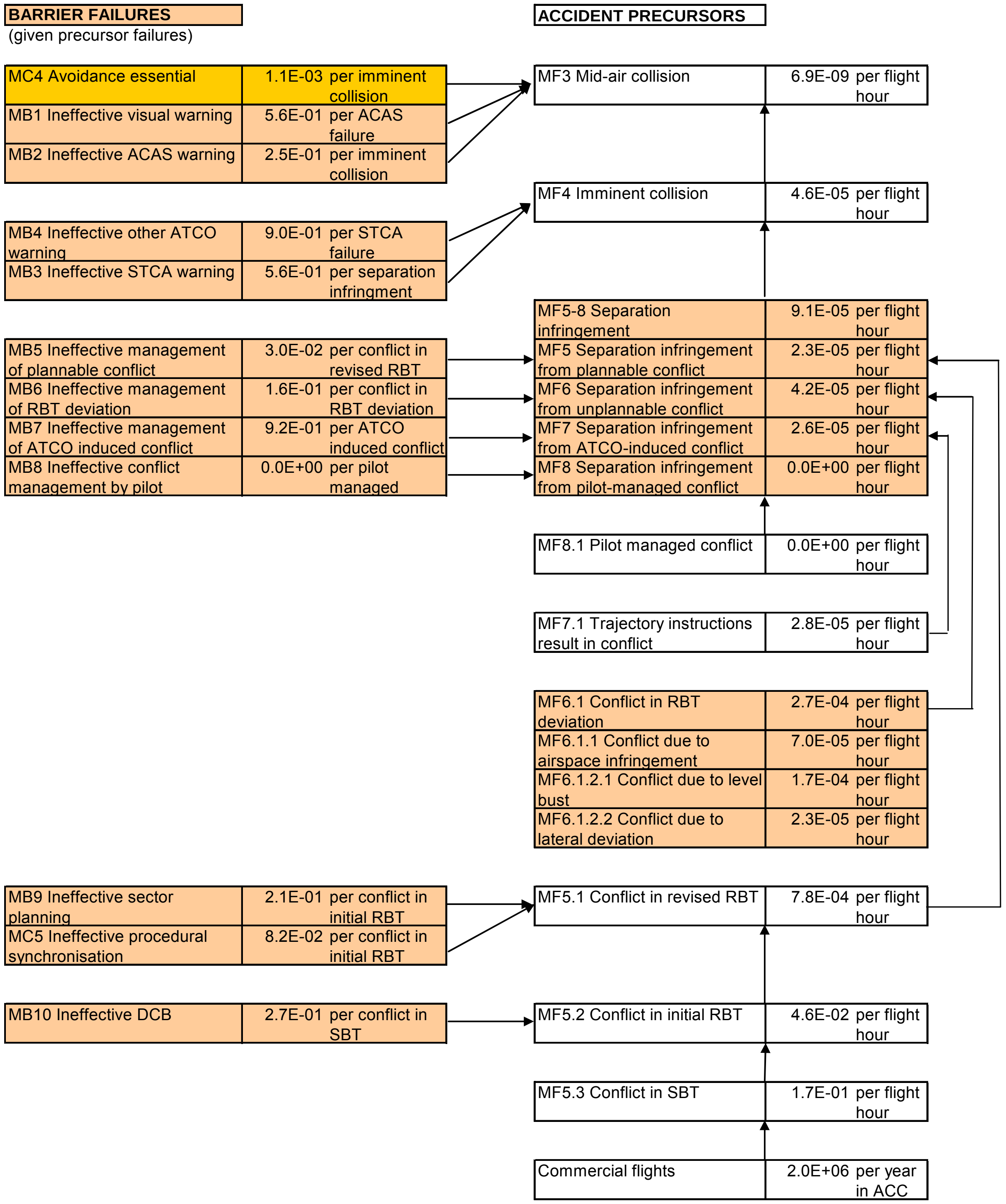


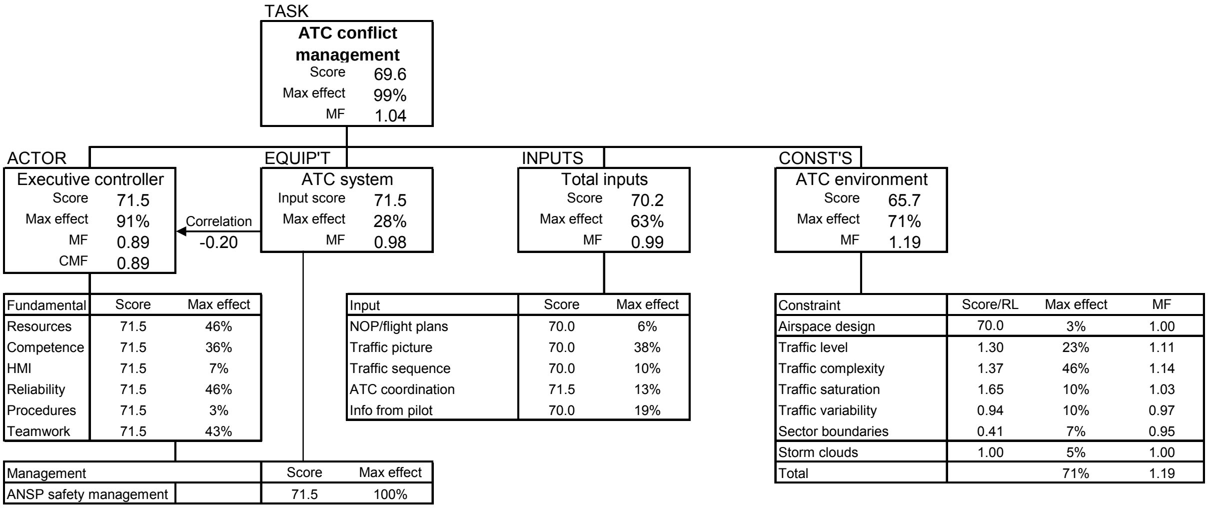
Table 21 shows the performance scores and modification factors for the tasks affecting mid-air collision. These are the main reason why the results above differ from other ACCs.

Table 21: Mid-Air Collision Management Tasks for En-Route ACC

TASK	PERFORMANCE SCORE	FRACTION OF BASE
ATC conflict management	69.6	1.037
ATC sector planning	69.7	1.030
ATC communication	69.4	1.058
ATC collision avoidance	67.2	1.177
ACAS warning response	70.0	1.000
Cruise/ climb/descent	70.0	1.002
Pilot visual mid-air collision avoidance	70.0	1.000

Figure 16 shows the reasons for these modifications, in the case of ATC conflict management. It indicates that the improved safety management is almost sufficient to offset the constraints of traffic level, complexity etc.

Figure 16: Influence Model for ATC Conflict Management in En-Route ACC



Fundamental	Score	Max effect
Resources	71.5	46%
Competence	71.5	36%
HMI	71.5	7%
Reliability	71.5	46%
Procedures	71.5	3%
Teamwork	71.5	43%

Management	Score	Max effect
ANSP safety management	71.5	100%

Input	Score	Max effect
NOP/flight plans	70.0	6%
Traffic picture	70.0	38%
Traffic sequence	70.0	10%
ATC coordination	71.5	13%
Info from pilot	70.0	19%

Constraint	Score/RL	Max effect	MF
Airspace design	70.0	3%	1.00
Traffic level	1.30	23%	1.11
Traffic complexity	1.37	46%	1.14
Traffic saturation	1.65	10%	1.03
Traffic variability	0.94	10%	0.97
Sector boundaries	0.41	7%	0.95
Storm clouds	1.00	5%	1.00
Total		71%	1.19

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

A comprehensive methodology for a unit-specific IRP has been developed. This enables to apportion all parts of the IRP fault tree model into generic airspace types, which can then be used to estimate the risk picture for any specific ATM unit. By checking the results against the original data, it is possible to verify that there are no obvious errors in the airspace-specific model construction.

In order to represent the characteristics of individual ATM units in more detail, an extensive set of influences has also been considered, and quantified where possible. This model in effect extends the existing IRP influence model to cover the main influences of the operating environment that are expected to vary between ATM units. However, due to a lack of suitable data, this unit-specific influence model necessarily makes extensive use of assumptions that at present cannot be validated. Its results are therefore extremely uncertain.

7.2 RECOMMENDATIONS FOR MODEL IMPROVEMENT

The following model development activities are recommended to improve confidence in the results:

- ECAC data on the flight time of IFR aircraft in different airspace types should be obtained to improve the estimates in Section 2.3.
- ECAC data on the flight time of IFR aircraft in different flight phases, and on the joint distribution of flight phase and airspace type, should be obtained to improve the estimates in Section 2.4.
- The dataset of collisions and loss of separation incidents should be expanded to reduce the uncertainties in the results in Section 3.
- A wider range of data describing differences between individual ECAC airspaces should be obtained to extend the influence model in Section 4.
- The relationships between proxy measures and model parameters should be based on structured expert judgement to replace the preliminary assumptions in Section 4.3.
- The face validity of unit-specific risk predictions in Section 5 should be confirmed using expert judgement.
- Estimates of the effects operational improvements in different airspaces should be obtained to ensure that the STAR tool gives valid unit-specific risk estimates.

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9 GLOSSARY OF TERMS

Term	Definition
ACAS	airborne collision and avoidance system
ACC	area control centre
ACE	ATM cost-effectiveness study
ADREP	accident/Incident Data Reporting
ANSP	air navigation service provider
APP	approach
ATC	air traffic control
ATCC	air traffic control centre
ATCO	air traffic control officer
ATFM	air traffic flow management
ATFCM	air traffic flow and capacity management
ATM	air traffic management
CAST	Commercial Aviation Safety Team
CCF	common cause failure
CFIT	controlled flight into terrain
CFMU	Central Flow Management Unit
CTA	control area
CTR	control zone
DCB	demand/capacity balancing
DL	division level
ECAC	European Civil Aviation Conference
ECCAIRS	European Co-Ordination Centre for Aviation Incident Reporting Systems
ECIP	European Convergence and Implementation Plan
EMF	exposure modification factor
E-TMA	extended terminal manoeuvring area
FL	flight level
FMS	flight management system
GA	general aviation
GDP	gross domestic product
GPWS	ground proximity warning system
ICAO	International Civil Aviation Organization
IFR	instrument flight rules
IMC	instrument meteorological conditions
IRP	Integrated Risk Picture
LAS	lower airspace

Term	Definition
MAC	Mid-Air Collision
ME	maximum effect
MF	modification factor
MSAW	minimum safe altitude warning system
MTCD	medium term conflict detection
MTOW	maximum take-off weight
MUAC	Maastricht Upper Area Control Centre
PS	performance score
RR	risk ratio
SESAR	Single European Sky ATM Research Programme
SMS	safety management system
SSR	secondary surveillance radar
STAR	Safety Target Achievement Roadmap
STCA	short term conflict alert
TMA	terminal manoeuvring area
TWR	tower
UAV	unmanned aerial vehicle
VHF	very high frequency
VFR	visual flight rules
VMC	visual meteorological conditions

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