Overall Safety Impact Results and User Manual

Marta Sánchez (Isdefe), Luca Save (Deep Blue)

A2COS safety certification

The objective is to model a macroscopic scenario for network-wide safety impact, enabling the estimation of the safety overall impact of introducing new Safety Enhancement Systems and/or operations in the total aviation system. The present document describes the research approach to address this issue, using ATM-NEMMO tool, a Network Macro Modelling tool for analysis of macroscopic behaviour of multi-component systems with complex interactions, in combination with a Causal model for Air Transport Safety (CATS). This deliverable also discusses four relevant selected Safety Enhancement Systems, the capacity of ATM-NEMMO to model them and potential scenarios defined by a user. Software modifications are done at a descriptive level. Finally, the document includes a User Manual on how to use ATM-NEMMO tool to support overall safety assessment.

Coordinator	L.J.P. Speijker (NLR)
Work Package Manager	S. Bravo Muñoz (APSYS)

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Acronyms

Acronym	Definition
ATM	Air Traffic Management
ATM NEMMO	ATM Network Macro MOdel
CODA	Central Office for Delay Analysis
DCB	Demand and Capacity Balancing
E-ATMS	European Air Traffic Management System
ECAC	European Civil Aviation Conference
EOBT	Estimated Off Block Time
ETA	Estimated Time of Arrival
ETO	Estimated Time Over
ETOT	Estimated Take Off Time
FMP	Flow Management Position
FTS	Fast Time Simulation
HDA	High Density Area
ICAO	International Civil Aviation Organization
NOP	Network Operations Plan
PCE	Probability of Change in ETOT
PFC	Probability of Flight Cancellation
PNF	Probability of New Flight
PI	Performance Indicator
ROT	Runway Occupancy Time
RT	Rotation Time
TAT	Turn Around Time
TIT	Taxi In Time
TMA	Terminal Manoeuvring Area
TOT	Taxi Out Time

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Executive Summary

The overall safety level of the total aviation system can be defined as an estimation of the safety performance of the network and the probability that safety issues occur. Building on the assumption that the degree of amplification and propagation of uncertainties throughout the ATM system has an impact on the probability of occurrence of safety issues, the discussion in this document explores the influence of the network performance on the level of risk of safety accidents/ incidents.

The network state is considered inn terms of

- Presence of congestion (demand exceeding capacity and leading to overloads occurrence);
- Network behaviour in terms of robustness (ability to hold back delay propagation) and resilience (ability to recover from states of generalised congestion with long delays spreading across several areas of the network).

Degraded situations with high congestion and large delays with long recovery times have an impact on Air Traffic Management aspects, such as controller workload, that at their turn are factors used to assess the probability of occurrence of safety events in the pathway of incidents.

In particular, it is discussed the evaluation, through modelling and simulation of the European ATM network, the overall safety impact of new ATM systems:

- The operational/ performance implications of the system/ operation under study are evaluated and linked to efficiency/ predictability enhancements and to potential reductions of the inherent uncertainties present in the ATM system;
- These enhancements/ uncertainty reductions are translated into ATM-NEMMO simulation tool input parameters. Results obtained are in terms of performance impact (overloads and delays) and delays propagation;
- These results are finally used as an input to safety assessment models in two possible ways:
  - Using network-wide average efficiency and predictability performance indicators as input to the safety models, obtaining overall safety impact results in line with the SESAR safety risk at network level;
  - Using local performance results as input to the safety models to identifying areas of the network that are highly at risk.

The simulation tool proposed is ATM-NEMMO, a mesoscopic approach to modelling European ATM network based on complex systems theory. The model response in the form of output variables (performance Indicators and metrics) is the input to a specific safety module, based on CATS safety causal model diagrams, able to translate the outputs in terms of safety level both at network and local levels.

The CATS safety module integrates links directly the outcomes of the simulations to the probability of occurrence of specific base events that are considered to be sensitive to changes in the level of delay and/ or overloads. The combination of ATM-NEMMO with CATS diagrams allows therefore that network-wide

performance assessments, capturing propagation patterns and integrating interdependencies between network elements, are transformed into potential variations of local safety risks, enriching the safety picture given by the CATS fault-tree approach.

The results of the ATM-NEMMO/ CATS analysis could be an input for safety practitioners to the analysis of the potential hot spots where countermeasures might apply.

Four Safety Enhancement Systems are considered, being new tools or operational concepts (including for example new procedures and operating methods) that are expected to have a positive impact on the Safety of the Total Aviation System. For each of them, two approaches are considered:

- **Success approach**, in which it is assessed how effective the new concepts and technologies would be when they are working as intended;
- **Failure approach**, in which the ATM system generated risks are assessed, i.e. induced by the ATM changes failing. This approach covers loss of the system and erroneous functioning and, in both cases, detected or undetected. In the present study the failure approach considered is **detected loss**.

To provide indications to the safety experts using the ATM-NEMMO/ CATS model with a complete picture of the safety implications of introducing the new Safety Enhancement Systems, considerations are included in two ways:

- On one side, the network performance results for the new system in operation are translated into changes in probabilities of occurrence of CATS base-events;
- On the other side, a generic safety impact of the new system/ operation is discussed since it might be also translated into changes in CATS diagrams, in terms of failure rates and improvement/ addition of safety barriers.

The results, in terms of overall safety level, can be obtained at network, airport or cluster level (for example, for a pre-defined set of airports). The results present the safety risk picture in terms of probability of occurrence of safety accident or incident for each of the seven end-states considered in ASCOS CATS diagrams:

- Runway excursion;
- Collision with ground;
- In flight break-up;
- Collision in mid-air;
- Collision on runway;
- Collision with ground;
- Collision on taxiway or apron.

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1 Introduction

1.1 Background and scope

The main goal of ASCOS WP3 is to develop a total aviation system safety assessment methodology, with supporting safety based design systems and tools, for handling of current, emerging and future risks. This safety assessment needs, not only to address the new risks, but to be adapted to the whole Total Aviation System. The safety analysis can as well be enlarged with the impact on the performance network by combining the ATM Network MacroMOdel (ATM-NEMMO) with Causal model for Air Transport Safety (CATS) diagrams. In this way it is possible to have an overview of the safety impact of the introduction of a novelty in the Total Aviation System.

The present document is the deliverable of ASCOS WP3.4 “Tool for overall safety impact”. It details how to perform an overall safety impact of the total aviation system linked to the introduction of new safety enhancement systems and/or operations. The document is focussed on the approach for this network-wide safety analysis, based on the use of a Network Macro Modelling tool that measures performance indicators which are subsequently used to assess the safety implications by integrating them into the Event Sequence Diagrams (ESD) and Fault Trees (FT) defined in WP3.2 CATS model [12].

1.2 Objectives

The WP3.4 main objective is to detail how to perform an overall safety impact assessment of the total aviation system linked to the introduction of new Safety Enhancement Systems and/or operations.

The study builds on the assumption that the propagation and amplification of uncertainties throughout the air transport system has an impact on the safety performance of the system. The approach is therefore to study the network delays and overloads (indicators of amplification and propagation of uncertainties) linked to different Safety Enhancement Systems, and to estimate their influence on the occurrence of safety issues at congested airports.

1.3 Intended Audience

The audience of this document is primarily the partners of ASCOS project, and in particular partners of WP3, work-package where WP3.4 activity is enclosed, and partners of WP4, as potential users of the theoretical approach detailed.

Besides, the discussions included in this paper address state-of-the-art research questions in the field of overall safety impact using modelling and simulation tools, and so they might be interesting for those researchers in the same line of investigation, either from the safety domain or from more basic research perspectives linked to the development of modelling and simulation models in the field of transport.

1.4 Structure of the Document

The document is structured as follows:

- Chapter 1 Introduction. This is the present chapter, introducing the document scope, intended audience, structure and links with other ASCOS work packages;
- Chapter 2 Technical Approach for Overall Safety Impact. It details the approach proposed to perform the network-wide safety analysis, based on the combined use of a Network Macro Modelling tool to measure performance indicators and a causal model for air transport safety based on Event Sequence Diagrams (ESD) and Fault Trees (FT).
- Chapter 3 Safety Enhancement Systems. It contains the description of the four Safety Enhancement Systems analysed in WP3.4, their estimated impact on the main KPAs and the associated input parameters that are would be used in the ATM-NEMMO tool to analyse both success and failure approaches linked to their implementation across the European air transport network.
- Chapter 4 Summary of Assumptions. It summarises the modelling and simulation assumptions linked to the evaluation of the overall safety impact linked to the introduction of new safety enhancement systems and/or operations in the total aviation system.
- Chapter 5 Modelling Scenarios. It describes the modelling scenarios that would be implemented in the ATM-NEMMO tool to simulate both nominal conditions and the occurrence of specific events.
- Chapter 6 Type of Simulation Results. The type of potential results obtained is described, as well as how the associated overall safety impact could be estimated.
- Chapter 7 Final Remarks. This closing chapter drafts recommendations about the way forward in the research line proposed in this document.

- Appendix A gathers the ATM-NEMMO tool technical specifications (main modules, flow diagrams, input and output parameters).
- Appendix B includes a user's guide with guidance on how to use the ATM-NEMMO/ CATS tool to support an overall safety assessment such as the one proposed in WP3.4.
- Appendix C analysis the link between ATM-NEMMO simulation outputs and the base-events in CATS diagrams.

1.5 Links with other Work Packages

The main link of WP3.4 is with ASCOS WP3.2, which develops the CATS model [12] and the associated ESD and FT diagrams. WP3.4 builds on these diagrams to translate the capacity, efficiency and predictability performance results of ATM-NEMMO into meaningful overall safety impact.

Besides, the theoretical results of WP3.4 are an input to WP4.5, which assesses the safety impact of bringing the proposed safety enhancements into operational use.

2 Technical Approach for Overall Safety Impact

2.1 Introduction: ATM Uncertainty Propagation and Safety Assessment

To analyse the contribution of Air Traffic Management (ATM) system to **air transport performance** using a large-scale perspective (transnational or at a global level), it is necessary to abstract and integrate the complex and heterogeneous ATM elements, without needing to include too much detail (which would be impractical or even impossible if dealing with the whole ATM system). A framework for developing global network models is complex network theory:

"Modelling of the ATM system with network theory to study its properties has been done in the past decade both at a worldwide level and at the national level. In these works, the airports are the nodes of the network whereas the flights are the links connecting these nodes. (…) But the idea of using these ATM network models to study topics such as such as efficiency, safety, or flexibility is very recent. (…) However, there seems to be a lack of works where the uncertainty is taken into account, which clearly identifies a research challenge at this macroscopic scale. (…) While it is evident that uncertainty has a significant impact in safety assurance levels, there have been few studies directly relating the effect of uncertainty (and its propagation) and safety levels." [2]

Modelling and simulation safety assessments in air transport are mainly focussed in continuous-time modelling of trajectories for evaluation of vehicles loss of separation and/ or technical and procedural resilience. To address the objective of performing an **overall safety impact** of the European total aviation system, the main constraint of current tools if the excessive computational intensity that would be required to model individual vehicles and/ or procedural interactions for a large-scale air transport network [3].

One of current technical trends in the line of research of overall safety impact using tools for simulating real operations is based in modelling techniques with non-deterministic and non-microscopic approaches. The line of research is built upon the **assumption** that propagation and amplification of uncertainties throughout the ATM system is directly linked to a decrease in the safety of the system, as it is stated in the following text extracted from the public position paper of the SESAR research network dedicated to the study of 'Mastering Complex Systems Safely'.

"*The future ATM system will demand a considerable improvement in safety levels; to obtain a significant increase in safety, new unconventional mechanisms will have to be developed. Moreover, the transition from the actual ATM paradigm to the future ATM system devised by SESAR will pose great challenges by itself that will require the creation of new tools to assess and ensure safety levels. One potential area of improvement in conventional safety assessment tools is the inclusion of uncertainties that are present in the ATM system. In this way,* ***once the mechanisms of uncertainty propagation throughout the ATM system are well understood, then control and management rules can be developed to avoid amplification of uncertainties that would greatly decrease the safety of the system****.*" [2]

Therefore, one possible way forward, derived from this state-of-the-art position paper, to analyse the overall safety impact of new operational changes is to assess their impact on the propagation and amplification of uncertainties throughout the ATM system, which is assumed to be directly linked to the safety performance of the system.

2.2 Overall Safety Level

Building on the assumption stated above, in which propagation and amplification of uncertainties throughout the ATM system has an impact on the safety performance of the system, the proposed approach is to study the **network delays and overloads**, as indicators of the level of amplification and propagation of uncertainties. The rational is the following:

- The air transport network is not a deterministic system: the actual execution of the planned flights cannot be accurately predicted from the traffic planning. These differences are linked to the existence of disturbances, which are **inherent uncertainties to the ATM system**. A disturbance is an event which produces variations from the planned operation of the air transport processes or elements. Disturbances or uncertainties are related to the variability associated to air traffic processes or elements and are inherent to the air traffic network, appearing under nominal conditions. Examples of internal disturbances are aircraft failure or variability of taxi-time. Internal disturbances account for all the potential sources of uncertainty in the air transport system. They are at the root of primary delays.
- The variations related to the existence of internal disturbances can be locally absorbed or can cause performance degradation in the form of disruptions: **delays, overloads**. A typical disruption is the appearance of flight arrival delays of more than 15 minutes, where a delay is the time lapse which occurs when a planned event does not happen at the planned time. The appearance of disruptions in the air traffic network means that inherent uncertainties are propagated and amplified, and that the network performance, including safety, is degraded.

The safety impact is therefore derived from the overload and delay propagation **and their influence on the occurrence of safety issues at congested airports**.

The **overall safety level** is defined as an estimation of the safety performance of the network and the probability that safety issues occur. This probability is influenced by several factors, and amongst them, by the network state in terms of presence of congestion (demand exceeding capacity and leading to overloads occurrence) and of network behaviour in terms of <u>robustness</u> (ability to hold back delay propagation) and <u>resilience</u> (ability to recover from states of generalised congestion with long delays spreading across several areas of the network). It is considered that <u>degraded situations with high congestion and large delays with long recovery times have an impact on Air Traffic Management aspects, such as controller workload</u>, that at their turn are factors used to assess the probability of occurrence of safety events in the pathway of incidents.

It must be highlighted that safety is a complex multi-dimensional subject, using diverse metrics that can show different behaviour and change at different rates. The definition of an overall "safety level" has been addressed in Air Traffic Management, in order to respond to SESAR safety performance target[1]. SESAR Safety Reference Material [16] refers to EPISODE3 project to interpret "*the x10 SESAR safety performance target very precisely*" and to supply "*the necessary detail*". In EPISODE3 "White paper on the SESAR safety target" [15] the preferred metric for the safety level is the probability of accidents per encounter. This choice is linked to the fact that the expected number of encounters varies with the square of the number of flights, since SESAR target includes the explicit assumption "*safety needs to improve with the square of traffic volume increase, in order to maintain a constant accident rate*". Furthermore, the paper refers to specifying the safety level per type of airport (e.g. large, medium and small) and airspace (differing characteristics of En-route and TMA airspace). In conclusion, and given the constraints of the definition of safety level for the specific purpose of responding to the SESAR safety target as defined in the reference used by EPISODE3 project, the overall "safety level" is understood as a probability of occurrence of certain specific safety events (accidents) across the different local-specific areas of the network.

In the current version of the SESAR ATM Master Plan [17], the target is further decomposed in two strategic objectives at network level where the Key Performance Indicators used are the number of accidents per annum and the safety risk per flight hour. For the second objective, the approach in EPISODE3 could be valid to build an overall (network) safety level from the local diversity of safety risks: weighting the contribution to network safety risk of each category of airport/ TMA by the expected distribution of ECAC traffic across them.

KPA	Key Performance Indicator (KPI)	Strategic Objectives (as compared to 2005)	SESAR Step 1 + Baseline Contribution (as compared to 2005)
Safety	Improve Safety performance by a factor of 10		
ECAC annual accidents	No increase in the number of accidents with ATM contribution per annum	No increase – irrespective of traffic growth	No increase – irrespective of traffic increase addressed by SESAR
Safety risk	Safety risk per flight hour	No increase - irrespective of traffic growth	-40%

Figure 1 Proposed SES Strategic Performance Objective for Safety KPA at European Network Level [17]

In the present discussion, the approach for evaluating through macroscopic simulation the overall safety impact of new ATM systems and operations in the air transport network is displayed in Figure 2. The operational/ performance implications of the system/ operation under study are evaluated and linked to efficiency/ predictability enhancements and to potential reductions of the inherent uncertainties to the system. These enhancements/ uncertainty reductions are translated into ATM-NEMMO simulation tool input parameters. Results obtained are in terms of performance impact (overloads and delays) and delays propagation. These results are then used as an input to safety assessment models in two possible ways:

[1] "Improve the safety performance by a factor of 10" while traffic increases 3-fold [15].

- Using network-wide average efficiency and predictability performance indicators as input to the safety models, obtaining overall safety impact results in line with the SESAR safety risk at network level;
- Using local performance results as input to the safety models to identifying areas of the network that are highly at risk.

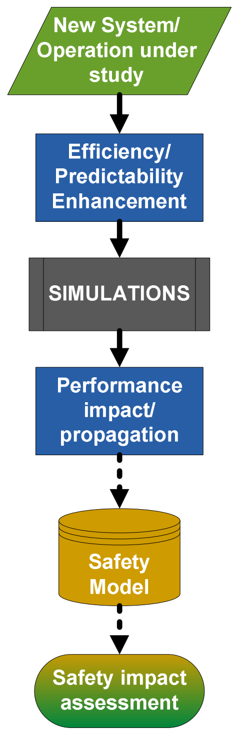

Figure 2 Approach for Overall Safety Impact

2.3 ATM-NEMMO Tool for Overall Safety Impact

ATM-NEMMO modelling and simulation tool analyses the air transport system exploiting a mesoscopic approach where probabilistic methods account for Air Transport Network microscopic details without losing the macroscopic and strategic view of the system. The inherent uncertainty of the air transport system performance is taken with stochastic parameters that account for all the potential sources internal to the air transport system: turnaround process of aircraft at airports, taxi and flight duration variability, etc. [1]

Appendix A includes the technical specifications of the ATM-NEMMO tool, picturing the main modules of the tool in flow diagrams and detailing input parameters and variables (or output parameters).

The approach for using ATM-NEMMO for overall safety impact is depicted in the figure below (Figure 3). According to it, in order to perform an overall (network-level) assessment of the impact of a specific new system or operation, this system/ operation is first translated into a variation in the input parameters to the model. The model response in the form of output variables (performance Indicators and metrics) is the input to a specific safety module, based on CATS model diagrams [12], able to translate the outputs in terms of safety level both at network and local levels, as it has been discussed in previous section.

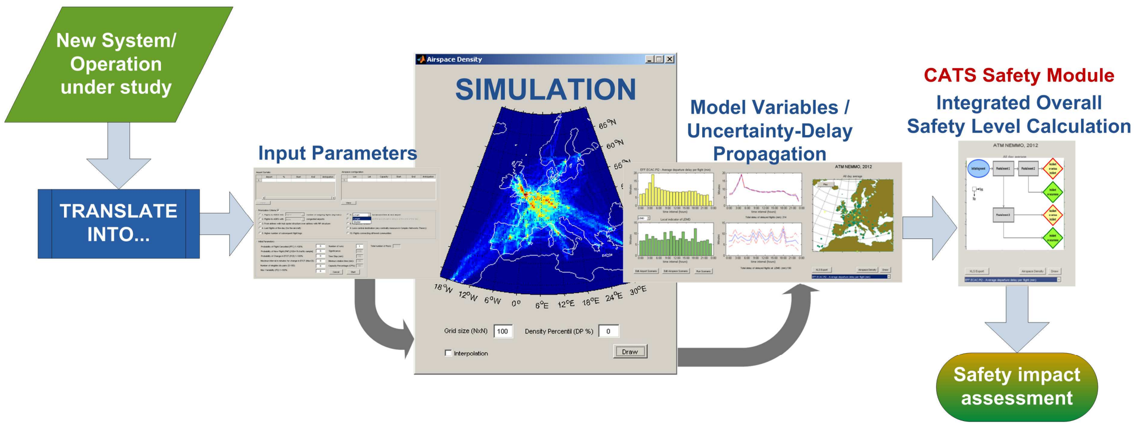

Figure 3 Overall Safety Impact Approach using ATM-NEMMO/ CATS tool

2.3.1 Input Parameters and Uncertainty

As commented above, Appendix A includes the technical specifications of the ATM-NEMMO tool, detailing input parameters. From the list of customisable parameters included in the model, the following are selected in the context of ASCOS for simulating the predictability/ efficiency enhancements linked to the new systems/ operations under study:

- Minimum rotation time – minimum time necessary between landing of a flight and take-off of the subsequent flight using the same aircraft. This is the time for taxiing-in, for the passengers to debark, for the aircraft cleaning, technical verifications, etc., for the boarding of passengers for the following flight and for taxiing-out;
- Probability of Change in ETOT (Estimated Take-Off Time) – is the % of flights that experiment a change in ETOT during short-term phase due to primary delay causes;
- Maximum interval in minutes for change in ETOT – indicates, in minutes, the maximum variation in ETOT during short-term phase, of those flights experimenting changes in ETOT allowed in the model;
- Maximum variability in flight duration – is the % of increase or decrease in flight duration that can be expected for all flights due to en-route variability related to wind, weather conditions, etc.;
- a1 – is the probabilistic distribution used to introduce uncertainty related to the ability of each flight to fulfil estimated times at the airport. It is based on statistics of primary delays at the airport.

Section A.3.3 of Appendix A provides more details about the rational to simulate uncertainty in the ATM system and how parameter a1 is calculated. As an example, in the case of the turnaround, a fixed rotation time is defined (considered as the minimum turnaround time required for each type of aircraft being modelled) and variability is included as a stochastic variable added to the fixed rotation time. This variable follows a probability distribution defined in line with available statistics of actual variability (or primary delays) of turnaround time at airports, and that can be customised to represent a particular "safety enhanced" situation of improved predictability.

2.3.2 Scenario Customisation

As it is described in Appendix A, airports and High Density Areas (HDA) in ATM-NEMMO are represented by their nominal, real and predicted capacities:

- Nominal capacity is equal to the hourly declared capacity of the airport;
- Real capacity of each airport/ HDA is changed during the simulation to reflect the real capacity of the airport at each Time Step, which can differ from the nominal data in "Airports" in the case of a capacity shortfall;
- Predicted capacity is used to indicate whether the information available in the network about the real capacity of the airport at a given Time Step is equal or not to the real capacity of the airport at that Time Step. In case a capacity shortfall is "visible" in the network, predicted capacity will be equal to nominal (real) capacity. In other case, predicted and nominal capacity might have different values.

Appendix B describes how capacity shortfall can be set in ATM-NEMMO. In the Airport Scenario Editor, the 'impacted airport' is selected in the field 'Name'. After, the percentage of capacity shortfall is introduced in '% field'. Both, the 'Start' and 'End' times are editable to define the period of time in which the capacity shortfall at the selected airport is active. Finally, the 'Anticipation' refers to the time in advance in which the 'Network' is informed about the capacity shortfall at the selected airport.

2.3.3 Model Results – Performance Indicators

From the model variables are obtained as **outputs of the simulations** (see Appendix A), ATM-NEMMO automatically calculates the following Performance Indicators that are proposed for their translation in terms of network overall safety level:

KPA	Performance Indicator (PI)	Local*	Global	Unit	Definition
Capacity	CAP.PI 2	X		Hourly throughput overloads	Number of occurrences of capacity (hourly throughput) overloads by overload level per sector/airport/ point. This indicator identifies bottlenecks and congested nodes.
Efficiency	EFF.PI 1	X	X	Percentage of flight departing on time	Hourly percentage of flights delayed at departure more than 3 minutes.

KPA	Performance Indicator (PI)	Local*	Global	Unit	Definition
	EFF.PI 2	X	X	Average departure delay per flight (min)	Hourly departure delay minutes divided between total number of departure flights. Delay minutes are added up only for "delayed flights": delayed at departure more than 3 minutes.
Predictability	PRED.PI 1	X	X	Percentage of delayed flights	Hourly percentage of flights delayed at arrival more than 3 minutes.
	PRED.PI 2	X	X	Average delay of delayed flights	Average delay of flights suffering delay of more than 3 minutes.
	PRED.PI 3	X	X	Reactionary delay (min)	Hourly departure delay minutes for delayed flights due to reactionary delay.

Table 1 ATM-NEMMO Performance Indicators for ASCOS

* Local: Airport and/ or High Density Area; Global: network-wide.

Besides, ATM-NEMMO produces different results at each simulation run, for the same given set of network static conditions (topology, capacities and planned traffic). This is related to the existence of the stochastic parameters permeating the performance of all elements and processes and producing different variability values in each simulation run. Each simulation run is repeated a significant number of times (Monte Carlo simulation) and results are obtained as empirical probability distributions. Statistical analysis allows obtaining the probability density, or the likelihood that a variable (performance indicator) being analysed displays a certain value.

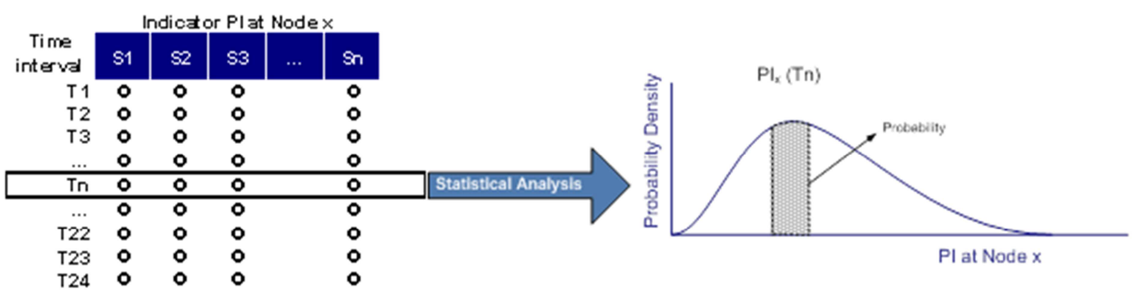

Figure 4 Indicator PI at node X. Probability distribution obtained through Monte Carlo simulation

The interest of these results is the characterisation, given certain initial conditions, of worst and best scenarios. The results can also answer the question of **how predictable the value of an indicator is** from the set of simulation responses produced:

- A scattered set of results (high standard deviation) indicates that, under the specific conditions imposed by the scenario, quite different responses of the network are possible, and that even the most likely response is not highly probable. The network behaviour is highly unpredictable;
- A concentrated set of results (low standard deviation) indicates that all possible responses of the network are close to the average response, which is a good prediction of the most likely response. The network behaviour is quite predictable.

2.3.4 CATS Safety Module

In order to translate the performance results (performance indicators and associated standard deviation) directly displayed by ATM-NEMMO into safety meaningful results, a safety module based on CATS causal model diagrams [12] is proposed.

The core of CATS causal model is formed by events that may lead to accidents/ incidents, and that can be described as hazards. A particular hazard can be caused by multiple root causes, and the failure of safety barriers after a hazard takes place also has root causes. To represent this, CATS model uses Event Sequence Diagrams (ESD) in combination with Fault Trees (FT), as represented schematically in Figure 5.

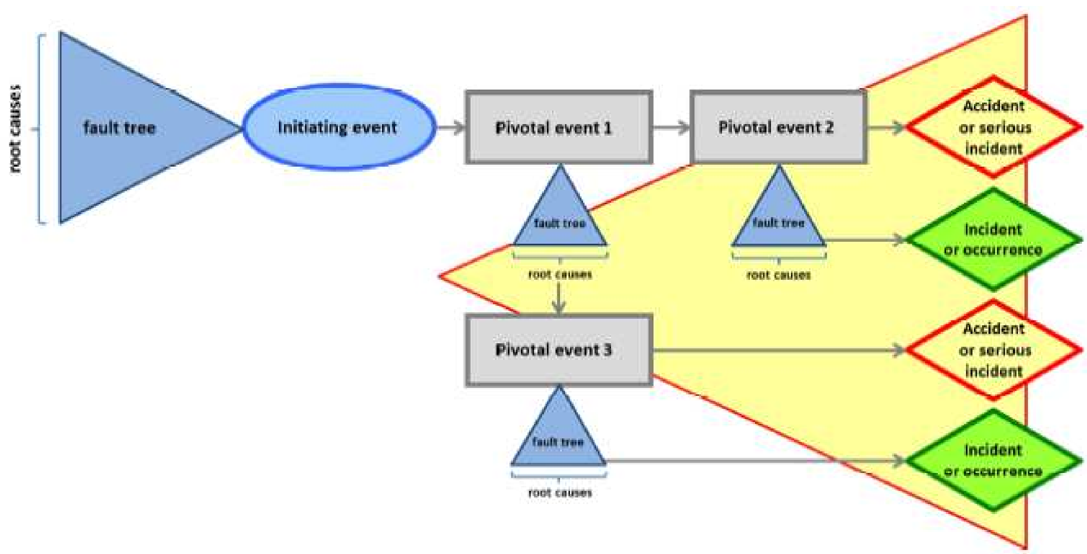

Figure 5 ESD with associated FT in CATS model [12]

Fault Trees are used to represent the root causes of both the initiating event and the pivotal events of an ESD. Each fault tree contains events that are stated as faults and are combined by logic gates, as shown in next figure.

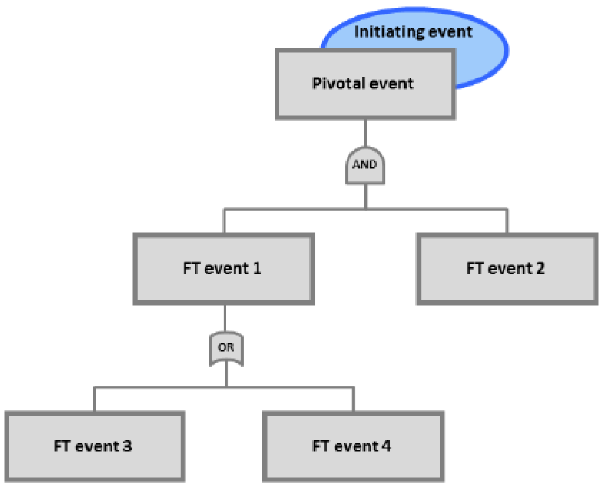

Figure 6 Generic Representation of a Fault Tree [12]

The quantification of accident scenarios in ASCOS project is done by assigning absolute probabilities to the initiating events of each ESD and conditional probabilities to the pivotal events, referred to the 'yes' branches of the events. This is illustrated in Figure 7.

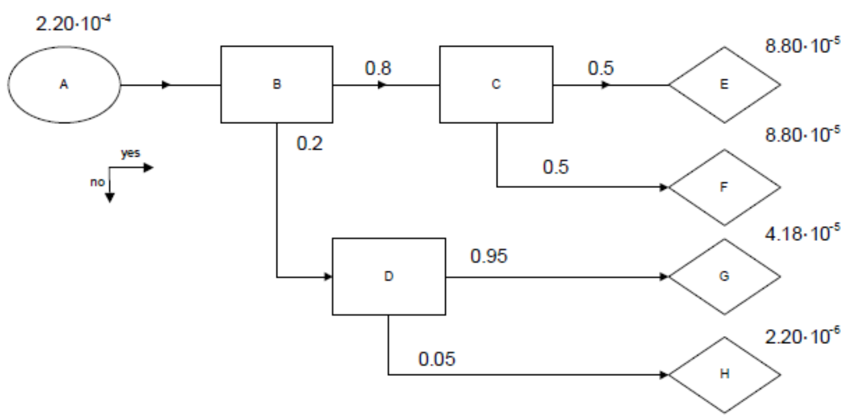

Figure 7 Generic Quantified ESD using Conditional Probabilities [12]

In ASCOS ESDs, most initiating and pivotal events have associated Fault Trees. In those cases, the probability of the initiating or pivotal event is associated to the probability of the top event of the Fault Tree, which at its turn is calculated by aggregating the probabilities of the FT base events through the logic gates.

The probability of the base events is determined by using historical air safety data, when available, by calculation using other quantified events (e.g. precursors) or by expert opinion.

In WP3.4, the theoretical development of a CATS safety module for ATM-NEMMO tool builds on the idea that the implementation of certain new systems/ operations in parts or the totality of the aviation system has an impact on the probability of occurrence of certain base events considered in ASCOS for quantifying the total risk picture. This impact is transmitted through the predicted changes that the new system/ operation produces in the delay/ overload picture. The CATS safety module integrates the ESDs and FTs developed and quantified in ASCOS WP3.2 and links directly the outcomes of the simulation (see section 2.3.2) to the probability of occurrence of specific base events that are considered to be sensitive to changes in the level of delay and/ or overloads. The combination of ATM-NEMMO with CATS diagrams allows therefore that network-wide performance assessments, capturing propagation patterns and integrating interdependencies between network elements, are transformed into potential variations of local safety risks, enriching the safety picture given by the fault-tree approach.

This rationale is depicted in Figure 8. For each scenario of implementation of a new system/ operation, a baseline scenario is set for comparison. The resulting value of each Performance Indicator (PI) is compared with the value of the same PI in the baseline scenario, from where the difference (either positive or negative) is calculated. Besides, this difference is weighted by the measured change in standard deviation (how predictable the value of the indicator is). A variation in standard deviation of x% will mean that the final increment (Δ) of the indicator considered for impact on the probability of base events is as follows:

Final increment (Δ)	Change in PI	Change in SD
y * (1+x)	+y%	+x%
	+y%	-x%
y *(1-x)	-y%	+x%
	-y%	-x%

Table 2 Final Increment of PI weighted by Change in Standard Deviation

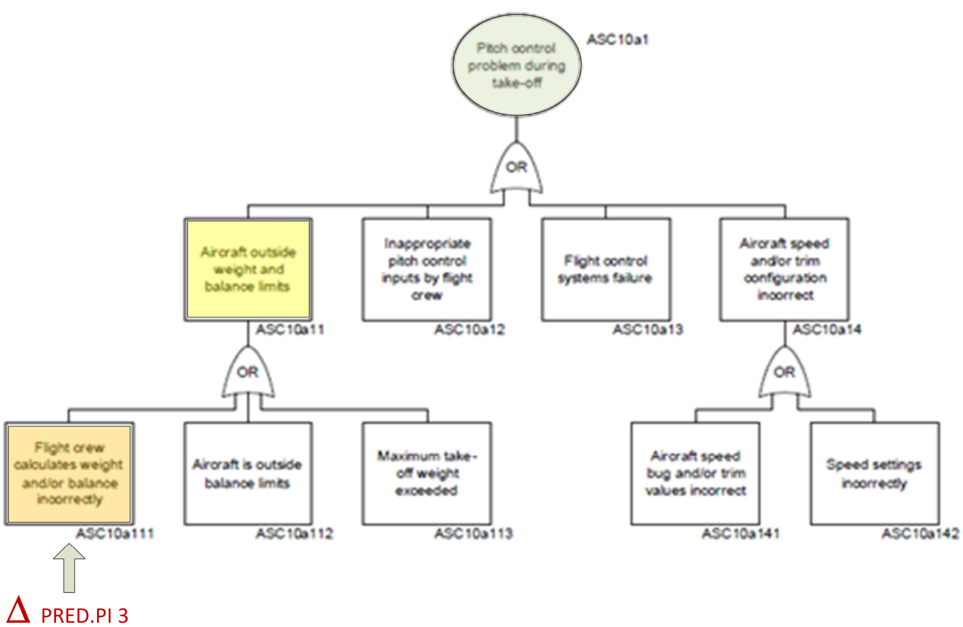

Figure 8 Example of Impact of Variation in Reactionary Delay (PRED.PI 3)

In the example above, the increment of PI PRED.PI 3 has an impact on the probability of occurrence of base event "Flight crew calculates weight and/ or balance incorrectly", and this probability variation is transmitted upstream up to the probability of the initiating event "Pitch control problem during take-off". Through the corresponding ESD, this probability is finally reflected in a change of the risk level that related end states occur (runway excursion, aircraft stops on runway and collision with ground).

An analysis of the influence of each ATM-NEMMO Performance Indicator on the CATS base-events is included in Appendix C. The analysis provides a rationale for each influence and an indication of positive or negative impact on the probability of the base-event considered. Quantification of these influences is leaved for expert judgement, where safety experts can customise the values in the tool according to the needs of their environment and type of assessment.

A description of the modelling scenarios considered is provided in section 5, and the details of the type of safety simulation results are included in section 6.

3 Safety Enhancement Systems

In the context of the present work, a *Safety Enhancement System* is a **new tool or operational concept** (including for example new procedures and operating methods) **that is expected to have a positive impact on the Safety of the Total Aviation System**. This definition also applies to those tools or operational concepts that have not been primarily designed for the purpose of enhancing safety but – due to their nature and way of changing operations – are expected to have a direct or indirect safety benefit on the Total Aviation System.

Examples of tools designed for the sole purpose of enhancing safety are the ground and airborne Safety Nets, such as the Short Term Conflict Alert (STCA) and the Airborne Collision Avoidance System (ACAS), which are deliberately not intended to contribute to other key performance areas than safety, such as the Capacity, the Efficiency and the Predictability of the Aviation System. On the other hand, other tools, such as the Medium Term Conflict Alert (MTCD) or the Advanced Surface Movement Guidance and Control System (A-SMGCS) for an Air Traffic Controller and the Graphic Route Display on an Airport Moving Map for a pilot, are designed to both enhance the Efficiency and Safety of operations. All these examples – as well as other possible examples of systems or procedures with a potential positive impact on Safety – will be equally considered as Safety Enhancement Systems in the present context.

The theoretical study proposed in this document is focussed on Safety Enhancement Systems as the new systems/ operations that are input to the overall safety assessment following the methodology described in Section 2 and generally depicted in Figure 3 in section 2.3.

The list of Safety Enhancement Systems for study in WP3.4 is included in the table below. The systems have been selected trying to cover as much as possible all flight phases and to consider both ground and airborne systems. The selection has been constrained by the availability of documentation describing the links between the systems and its impact on Safety and on other KPIs.

	Safety Enhancement System	Flight Phase
1	A-SMGCS (Advanced-Surface Movement Guidance and Control System)	Taxi out/Take Off
2	Brake to Vacate	Landing/ Taxi in
3	ASPA-IM-S&M (Airborne Spacing – Interval Management - Sequencing & Merging) Application	TMA
4	ATSAW-ITP (Airborne Traffic Situation Awareness - In-trail procedure)	En Route

Table 3 List of Safety Enhancement Systems

The following subsections are dedicated to the description of each Safety Enhancement System considered and to the input parameters used to implement them in the model. For each of them, two approaches are considered:

- **Success approach**, in which it is assessed how effective the new concepts and technologies would be when they are working as intended. This is concerned with the positive contribution to aviation safety that the ATM changes make in the absence of failure [16];
- **Failure approach**, in which the ATM system generated risks are assessed, i.e. induced by the ATM changes failing. This is concerned with the negative contribution to the risk of an accident that the ATM changes might make in the event of failure(s), however caused [16]. This approach covers loss of the system and erroneous functioning and, in both cases, detected or undetected. In the present study the failure approach considered is **detected loss**,

The subsections dedicated to each Safety Enhancement System start with a discussion about the impact of the new system into Key Performance Areas, which is later on translated into the input parameters associated to the success approach. An expected generic impact on safety is also included. The aim is to provide indications to the safety experts using the ATM-NEMMO/ CATS model to customise the CATS diagrams:

- On one side, the network performance results for the new system in operation are translated into changes in probabilities of occurrence of CATS base-events;
- On the other side, the generic safety impact might be also translated into changes in CATS diagrams, in terms of failure rates and improvement/ addition of safety barriers.

The customised CATS diagrams in the CATS module, in combination with ATM-NEMMO performance results, form the tool to perform a complete overall safety assessment of the Safety Enhancement System.

3.1 A-SMGCS Safety Enhancement System

The present description is focussed on the Advanced Surface Movement Guidance and Control System (A-SMGCS) Safety Enhancement System [7]. For the analysis of the impact on overall safety of this system, it is considered that the level 2 capabilities are complemented with the enhanced Surface Management as it is under development in the SESAR ATM Masterplan up to the defined implementation level 4 [4].

The A-SMGCS system, as currently studied in the SESAR Development Phase, is composed of 2 main functions:

- The A-SMGCS Routing and Planning;
- The A-SMGCS Guidance.

The **A-SMGCS Routing and Planning** covers the 2 following sub-functions:

- the **generation and assignment of a planned taxi route;**
- the **provision of the corresponding taxi time**.

The objectives of these services are to calculate the most suitable route on the movement area for an aircraft or a vehicle taking into account inputs from Air Traffic Control Officers (ATCOs) and known constraints such as taxiway closures, aircraft type, etc. The route definition corresponds to the Manual, Semi-Automatic and

Automatic modes as defined in ICAO A-SMGCS Manual Doc. 9830. The routes can be defined with a Manual, Semi-Automatic or Automatic modes as defined in ICAO A-SMGCS Manual Doc. 9830.

On the other hand, the **A-SMGCS Guidance** covers the 3 following sub-functions:

- The **Data-link transmission of a 'Cleared and Pending Taxi Route' (D-TAXI service)** to Flight Crews or to vehicle drivers;
- The provision of supplementary means of guidance on ground with an **increased level of automation of Airfield Ground Lighting (AGL)**;
- The **enhanced guidance means on-board of the aircraft (Airport Moving Map and Combined Vision System)** to provide Flight Crews with better situational awareness.

The general aim of these sub-functions is to increase the awareness of controllers, pilots and vehicle drives on the traffic situation picture – including low visibility conditions – and to provide guidance additional to the usual out-of-the window scan for an efficient execution of taxiway operations.

3.1.1 A-SMGCS Positive Impact on SESAR KPAs

The first function of A-SMGCS (**Routing and Planning**) is expected to have an impact on all the SESAR Key Performance Areas: Safety, Predictability, Capacity, Efficiency and Environmental Sustainability.

For what concerns the **Predictability**, there is an expectation that the **generation and assignment of a planned taxi route** as well as the automatic **provision of the corresponding taxi time** will have a positive impact on the **taxi-time accuracy and stability**. This in turn is expected to have a positive impact on the ATM system Predictability, thanks to the possibility to achieve an increased number of Controlled Take-off Times (CTOTs) and to reduce the variability connected to the 'first-in-first-out' principle which is currently prevailing in the management of Airport Operations.

This function is also expected to have a positive impact on **Efficiency**. There is an expectation that the support (manual, semi-automatic or automatic) provided to the generation of planned taxi routes, will reduce the ATC workload, thus reducing the dependence on ATCO constraints and making more efficient the taxing operations. This ultimately contributes to the objective of **reducing taxi times** (including ground queuing during taxi-in and taxi-out) linked to the temporal efficiency focus area.

In a similar vein, the other main function of A-SMGCS (**Guidance**) is expected to have a positive impact on both **Safety** and **Capacity**, thanks to the possibility to conduct taxiing operations in all weather conditions, including those with lower visibility.

3.1.2 Potential A-SMGCS Negative Impact on the Efficiency of the ATM System

When trying to anticipate the benefits of A-SMGCS in terms of the Predictability of the ATM system (and as a consequence on the overall Aviation system), it must be also considered that there might be, in certain cases, potential negative side effects on the flexibility of operations, leading ultimately to a decrease of Efficiency.

The A-SMGCS will have the possibility to monitor the speed of different aircraft during taxi operations and in combination with the Departure Manager function (DMAN) will calculate a precise taxiing time for each specific aircraft. Therefore one of the hypothesis currently under study is the possibility to impose a predefined taxi speed to all aircraft and vehicles to improve the predictability of taxiing and take-off operations, with the benefit of ensuring a good compliance with the TTOTs (Target Take-off Times) and a greater stability of the RBT (Reference Business Trajectory) associated with each flight. However, imposing a precise taxi speed to each flight may result counterproductive in case of erroneous deviations of one or more aircraft from the planned taxi-route, causing a perturbation in nominal taxiing operations; in case a flight is obliged to wait in a queue behind another aircraft, also to maintain the agreed departure sequence, the crew of such flight will obviously need to stop the aircraft or slow it down below the theoretical speed. In addition an imposed taxi speed will reduce the opportunities for recovering from delays by increasing the speed and taking advantage of possible gaps in the sequence. In conclusion there is a concrete risk that this lack of flexibility will in the end be detrimental to the efficiency of taxiing operations.

This potential trade-off between planning and flexibility and therefore between the Predictability of the ATM System on one side and the Efficiency and Capacity of it on the other side, will be duly considered when deriving assumptions on the best way to set parameters on the ATM-NEMMO tool in relation to the A-SMGCS example.

3.1.3 Expected Generic Impact on Safety

EUROCONTROL network unit has developed a preliminary safety case of A-SMGCS levels 1 & 2 [13]. It is based on a number of assumptions and on the case-study London Heathrow.

The A-SMGCS preliminary safety case shows that the safety requirements for A-SMGCS Level 1 and 2 can be implemented. The level 2 performance was assessed incorporating improvements in the rate of runway incursion monitoring false alerts, which can be seen as an improved performance of the Level 2 alerting function.

Besides, EUROCONTROL analysis states that A-SMGCS surveillance functions provide enhanced safety and protection of the runway as one means for avoiding runway incursions. A-SMGCS allows for enhanced low visibility operations as, with the appropriate certification, the identification of aircraft can be obtained directly from the HMI (European region). Although no dedicated studies have been conducted it can be assumed that the use of A-SMGCS may provide for maintaining higher levels of traffic during low visibility operations, thus minimising the negative capacity impact of such operational conditions.

In [14], simulations have demonstrated that A-SMGCS provides a situation less prone to error occurrence as a result of increased controller availability and the reduced number of time-critical actions.

3.1.4 Success Approach: Input Parameters to ATM-NEMMO linked to A-SMGCS Operation

The envisaged impact of A-SMGCS on SESAR Key Performance Areas, as discussed in previous sections, can be summarised as follows:

- General positive impact on Predictability, in the form of better taxi-time accuracy and stability;
- General positive impact on Efficiency, in the form of reduced taxi-times;
- Potential negative impact on Efficiency due to lack of flexibility (predefined taxi speed) when:
  - One aircraft deviates from taxi-route, and then the rest, to recover, are obliged to the predefined taxi speed, counteracting the reduction on taxi-time provided by the routing and planning function.

Based on these inputs, it is assumed (see section 4) that the general positive impact of A-SMGCS implementation at an airport is applicable to all flights departing from/ arriving to that airport, and that it is articulated in the form of **reduced variability of taxi-time** and a general **reduction of taxi-time**. However, when an aircraft deviates from planned taxi-time above a certain threshold, there is a negative chain reaction impacting the whole queue of taxiing-out/ in aircraft at the airport, being this in the form of increased taxi-times for all aircraft during a period of time at least equal to the average taxi-out/ taxi-in time of the airport.

The link with ATM-NEMMO input parameters is particularised below.

Reduction of taxi-time.

Minimum Rotation Time – minimum time necessary between landing of a flight and take-off of the subsequent flight using the same aircraft. This is the time for taxiing-in, for the passengers to debark, for the aircraft cleaning, technical verifications, etc., for the boarding of passengers for the following flight and for taxiing-out.

The MRT used in ATM-NEMMO is calculated according the following formula:

RT= TIT+ TAT + TOT

Where:

- TIT: Taxi In time is the time to go from the runway to the parking position, in absence of average data of Taxi Times for European Airports, these times are considered:
  - For Small/medium airports (airports with a capacity below 30 flights/hour) : 5 minutes;
  - For Big Airports (airports with a capacity over 30 flights/hour): 10 minutes.
- TAT: Turnaround Time- Preparation Time: It includes the time to disembark, cleaning, refilling of fuel, technical verifications and boarding, this time is dependant of the size of the aircraft and the type of carrier (for low cost carriers, less time to prepare the aircraft is considered).
  - For Low cost companies, Narrow body aircrafts: 20 minutes;
  - For Normal companies, Narrow body aircrafts: 30 minutes;
  - For Low cost companies Wide Body aircrafts: 40 minutes;

  - For Normal companies, Wide body aircrafts: 50 minutes.
- TOT: Taxi Out Time: is the time to go from the parking position to the runway. For simplification, same times than for TIT is used.

In the absence of percentage estimations for the reduction of taxi-time given by the implementation of A-SMGCS, it is assumed that a reduction of 20% applies.

Reduced variability of taxi-time.

Parameter a1 – is the probabilistic distribution used to introduce uncertainty related to the ability of each flight to fulfil estimated times at the airport. The approach to categorise internal disturbances followed in ATM-NEMMO with the purpose of introducing this "uncertainty" is to cluster them according to flight phases delimited by flight milestones. The milestones used are partially extracted from those defined in A-CDM [5]: milestones selected are related to physical positions of the aircraft throughout the flight taking the airport as a reference. Additionally, two other milestones, not included in A-CDM, are added: Runway Start Time (aircraft at start of runway) and Out of Runway Time (aircraft exits runway). Flight phases considered are: approach, landing, <u>taxi-in</u>, turn-around, <u>taxi-out</u>, take-off, ascent and en-route.

a1 is based on statistics of primary delays at the airport. Given that available data in CODA [6] that can be used to characterise the probabilistic distributions are aggregated by CODA cause (airline, airport, en-route, governmental, weather, miscellaneous), the approach in ATM-NEMMO is to aggregate as well all sources of internal disturbances during flight rotation.

Impact in terms of length of primary delay (minutes) of causes considered	Probability that a primary delay of this length occurs
On time	62%
5-15 minutes	21%
16-30 minutes	9%
31-60 minutes	5%
>60 minutes	3%

Table 4 Probability Distribution for ATM-NEMMO Parameter a1

In the absence of percentage estimations for the reduction of taxi-time variability given by the implementation of A-SMGCS, it is assumed that the probability that a primary delay of 5-15 minutes occurs at the airport is divided by two. The reduction is proposed to be applied to the 5-15 minutes range, given that primary delays related to variability of taxi-time fall within that length range.

Reduced flexibility during taxi.

When, given the probabilistic distribution set for **a1**, a primary delay of 5-15 minutes occurs, the same parameter can be used to account for the chain reaction related to the planning vs. flexibility issue during taxi. In that case, all subsequent departing aircraft at the airport within the same Time Step are assumed to experiment also a primary delay within the range of 5-15 minutes. The Time Step used in ATM-NEMMO is set to 15 minutes, which is a period of time at least equal to the average taxi-out/ taxi-in time of an airport.

3.1.5 Failure Approach: Detected loss of A-SMGCS

In this section it is considered a failure approach of the implementation of A-SMGCS, where a malfunction of the system leads to turning it inoperative either by the operator or by the system itself. This case is a detected loss of the A-SMGCS Safety Enhancement System.

To simulate this situation, ATM-NEMMO uses the functionality of scenario customisation, where capacity shortfalls can be defined (see section 2.3.2).

The rationale for using a capacity shortfall to simulate a detected loss of A-SMGCS is the following:

- Since A-SMGCS is implemented at a certain airport, it is assumed that the performance benefits of reduced taxi time and reduced variability of taxi time allow a planning of the resources taking into account an increased predicted capacity;
- At the time of operation, however, the A-SMGCS is lost and it turns out that the actual resources needed to operate are more than expected, since real taxi-time is higher than predicted and variability is as usual;
- This situation represents a **virtual capacity shortfall**, with no anticipation, i.e., that was not known to be happening in advance.

In terms of ATM-NEMMO simulation, the detected loss is translated in a capacity shortfall with no anticipation at the airports where the detected loss occurs. According to [14], there is an indication from Real Time Simulations that A-SMGCS implementation can provide an increase in movement rates in all conditions of between 5% and 15%. Based on these results, the virtual capacity shortfall associated to detected loss of A-SMGCS is set to 10% for implementation of ATM-NEMMO.

Additionally to the simulation of a failure approach through ATM-NEMMO features, a complete analysis of this case should take into account the impact of A-SMGCS detected loss on the quantification of CATS diagrams. A loss of the A-SMGCS implies loss of capability of assigning taxiways or of assigning correct times during taxi. This capabilities loss, if combined with lack of controller expertise (which can be expected for operators used to the A-SMGCS and associated workload decrease), can lead to a situation with increased probability of the ATCO issuing erroneous taxi time or taxi route, Moreover, other factors can further contribute to increase the of risk of collision in taxi, like lack of visibility from tower or lack of visibility of the pilot..

3.2 Brake to Vacate Safety Enhancement System

The Brake-To-Vacate (BTV) is an Airbus innovation in pilot aid to ease airport congestion and improve runway turnaround time [10]. It helps reducing taxiing time at busy airports by optimizing the runway occupancy time and lowering braking energy while maximizing passenger comfort.

The BTV system allows pilots to select the appropriate runway exit during descent or approach preparation. The system uses the GPS (Global Positioning System), Airport Navigation, Auto-Flight and Auto-Brake Systems to regulate deceleration, enabling the aircraft to reach any chosen exit at the correct speed in optimum conditions.

3.2.1 Impact on SESAR KPAs

In everyday operations, analysis shows that the auto-brake system used in nowadays operations cannot be adapted to each landing situation, which has specific touchdown characteristics (position and speed) with respect to the desirable exit taxiway foreseen by the crew (type, position and speed). Innovative solutions are urgently required because congestion is already a serious issue at some airports and because the airport's airside system capacity is significantly influenced by the runway capacity. The BTV system has therefore the potential to significantly reduce the total amount of delays at airports by decreasing Runway Occupancy Time (ROT) and thus **increasing runway Capacity**.

Studies have shown that depending on the traffic mix (various aircraft types), runway capacity can be increased between 5% (in the case of single-runway airports) and 15% (multiple-runway airports) by reducing ROTs. A remarkable example is the 19% capacity increase achieved over a period of three years on the single runway at Manchester, U.K. [10]

In case of low visibility, the benefits can be even higher, since runway capacity is drastically reduced due to lack of the operational guarantee between the pilot and the controller and the necessary increase of safety margins in separation between two consecutive aircraft. But the ATM operational gain based on the increase of runway technical capacity means that, in case of low visibility conditions, standard separation can still be reached thanks to BTV system.

The optimisation of arrival flows thanks to the use of BTV can be also read in terms of **improved Predictability** of landing operations. The ‘approach’ controller manages arrivals sequencing aircraft in final approach in order to optimize the arrival flow with respect to the runway occupancy time. The forecasted timing on a given future position on the approach trajectory (in this case runway exit) can be fulfilled more precisely thanks to BTV, which constitutes an improvement in **arrival punctuality** (on-time operations). The most visible gains will be obtained on the delays reduction occurring during airport saturation periods. Operation gains can then be magnified by a network effect.

3.2.2 Expected Generic Impact on Safety

The use of Brake to Vacate system ensures a safety improvement by increased crew situation awareness achieved with the in-flight landing distance computation continued on final approach and ground roll, even with low visibility operations.

BTV is coupled to a Runway Overrun Protection System (ROPS) supporting the prevention of runway excursion risks at landing. It consists in ROW (Runway End Overrun Warning) that triggers alerts during approach if the runway will be too short for landing, and ROP (Runway Overrun Protection) that triggers messages for pilot actions after touch-down and can automatically activates max pressure braking if needed.

The implementation of a runway overrun prevention device integrated in BTV, covering most frequent cases on non-contaminated runways, implies a notably safety increase. The complementary Runway Overrun Warning (ROW) & Runway Overrun Prevention (ROP) system computes realistic operational landing distances and compares them to the available landing distance in real time, while accommodating factors including: aircraft velocity, position, altitude and weight; runway conditions; ambient temperature and wind; and runway elevation. The "ROW" forewarns the pilot, either, if the aircraft is approaching a runway which is deemed “too short”, or, if the remaining runway length becomes too short.

3.2.3 Success Approach: Input Parameters to ATM-NEMMO linked to BTV Operation

The envisaged impact of BTV on SESAR Key Performance Areas, as discussed in previous sections, can be summarised as follows:

- General positive impact on Predictability, in the form of better **improved arrival punctuality**;
- General positive impact on Capacity, in the form of **reduced Runway Occupancy Time**.

The link with ATM-NEMMO input parameters is particularised below. It is considered also interesting for the design of the modelling scenarios associated to this SEnS to include situations where external events lead to low visibility conditions in order to compare the potential benefits in relation to the baseline scenario. It is expected than under low visibility conditions the benefits provided by BTV with regards to the baseline scenario are higher than in nominal conditions.

Improved arrival punctuality.

Parameter a1. This parameter is described in section 3.1.3.

In the absence of percentage estimations for the improvement of arrival punctuality given by the implementation of BTV, it is assumed that the probability that a primary delay of 5-15 minutes occurs at the airport is divided by two. The reduction is proposed to be applied to the 5-15 minutes range, assuming that primary delays related to arrival punctuality linked to missed runway exit fall within that length range.

Reduced Runway Occupancy Time.

It is assumed a reduced ROT generalised in all airports in the network due to the presence of better equipped aircraft in a high percentage. This is directly translated into an increase in runway capacity at airports, and given that runway capacity is considered the main limiting factor for airport capacity (see [ASU-4] in section 4), it is assumed that a reduced ROT in all airports can be simulated as a general increase in **airport hourly throughput capacity** of 5% (in the case of single-runway airports) and 15% (multiple-runway airports). These figures are coming from discussion in section 3.2.1.

3.2.4 Failure Approach: Detected loss of Brake to Vacate

A detected loss of Brake to Vacate system means that the runway occupancy is increased in seconds per operation. The reason is related to the pilot need to manually adapt the aircraft configuration to the runway exit. It is therefore more likely that the aircraft miss the runway exit, and needs a re-routing, increasing controller workload. In case of bad weather condition, cross wind, etc., Fthe pilot will find more difficulties to adapt the aircraft speed, increasing pilot workload, leading to a situation of non-smooth brake and increasing the probabilities of missing the runway exit.

The associated apparently small increase in ROT is not trivial, since aircraft that unnecessarily occupy the runway for additional seconds potentially provoke delays of at least one order of magnitude greater, (i.e. close to the minute or worse). If this develops into a domino effect, then overall system capacity will be reduced, causing losses of slots [10].

The loss of Brake to Vacate system would occur at the level of individual aircraft. A landing flight can experience a detected loss of the system, and the probability that this happens is related to the failure rate of Brake to Vacate.

The way to simulate this using ATM-NEMMO is a random increase in parameter a1 (section 3.1.3.) for a number of landing flights up to certain percentage. The increase is proposed to be applied to the 5-15 minutes range, assuming that primary delays related to arrival punctuality linked to missed runway exit fall within that length range.

The discussion about the failure rate of BTV is leaved to the safety expert using the model. It must be highlighted that it is typical for aircraft design and maintenance that only a few failure cases are available, not enough to get an accurate estimate. This is linked to the reliability of aircraft components. In certain cases, as it could be the case for BTV, there are not yet failure statistics, so expert estimates with similar components are used. One of the benefits of CATS diagrams is indeed to enable safety practitioners to re-create new environments and to obtain results for situations for which there are not yet statistical data available.

Besides, it could be the case for Brake to Vacate that the failure rate is low enough as to be negligible in terms of number of failures in a day of operation. In that case, the recommended use of ATM-NEMMO to simulate a detected loss of BTV system is the customisation for a simulation of longer periods of time, using the adequate traffic samples.

3.3 ASPA-IM-S&M Safety Enhancement System

The ASPA-IM-S&M (Airborne Separation Application – Interval Management – Sequencing and Merging) establishes a set of procedures aimed at enabling a controller to instruct the IM Aircraft to achieve and maintain a given time spacing from a preceding aircraft (called Target Aircraft). Both controllers and flight crew are provided with CWP and flight deck based ASAS tools to assist them in achieving and maintaining different kinds of spacing manoeuvres.

3.3.1 Impact on SESAR KPAs

The implementation of ASPA manoeuvres in final approach is expected to **improve the runway throughput** thanks to:

- a better adherence to the maximum runway throughput,
- a consistent **runway capacity** utilisation under all wind conditions.

In addition, the ASPA-IM-S&M involves the definition of working methods that - taking advantage of cockpit assistance/automation related to the spacing and merging functions - will enable more predictable arrival procedures to be achieved. The close adherence to time based spacing on final approach is expected to improve **landing time predictability**.

3.3.2 Expected Generic Impact on Safety

The safety benefits expected from the use of ASPA-IM-S&M system are related to:

- A reduction of controllers' task load;
- An increase of traffic situation awareness for both controller and pilot; and
- A reduction in the amount of controller-pilot communications, which reduces the potential for misunderstandings or for issuing inadequate instructions.

Moreover, in a scenario of traffic growth for IFR flights, this can be translated into no increase in the accident/ incident rate despite the traffic increase, and in particular for accidents induced by mid-air collisions in TMA, wake Vortex and losses of control in flight.

3.3.3 Success Approach: Input Parameters to ATM-NEMMO linked to ASPA-IN-S&M Operation

The envisaged impact of ASPA-IN-S&M on SESAR Key Performance Areas, as discussed in previous sections, is analysed in terms of capacity and predictability benefits:

- General positive impact on Predictability, in the form of better **improved arrival punctuality**;
- General positive impact on Capacity, in the form of **improved Runway throughput**.

The link with ATM-NEMMO input parameters is particularised below. Similarly to the discussion for BTV system in section 3.1.5, for the design of the modelling scenarios associated to this SEnS, it will be considered the study of non-nominal conditions linked to adverse wind conditions, where increased benefits of the ASPA systems are expected as compared to the nominal situation.

Improved arrival punctuality.

Parameter a1. This parameter is described in section 3.1.3.

In the absence of percentage estimations for the improvement of arrival punctuality given by the implementation of ASPA, it is assumed that the probability that a primary delay of 16-30 minutes occurs at the airport is divided by two. The reduction is proposed to be applied to the 16-30 minutes range, assuming that primary delays related to arrival punctuality linked to TMA manoeuvres fall within that length range.

Reduced Runway Occupancy Time.

It is assumed an improved runway throughput generalised in all airports in the network due to a better approach sequencing. This is directly translated into an increase in runway capacity at airports, and given that runway capacity is considered the main limiting factor for airport capacity (see [ASU-4] in section 4), it is assumed that an improved runway throughput in all airports can be simulated as a general increase in **airport hourly throughput capacity** of 5%.

3.3.4 Failure Approach: Detected loss of ASPA-IM-S&M

The consequences of a detected loss of the ASPA-IM-S&M system operating at a given airport are reduction of safety margins, increase in controller workload (and the subsequent distress) and loss of flight efficiency. The situation is translated into a reduction in the number of landing flights per hour at the airport, in order to match the workload/ flight efficiency limitations with the number of flights that can be safely managed.

To simulate this situation, ATM-NEMMO uses the functionality of scenario customisation, where capacity shortfalls can be defined (see section 2.3.2). The situation represents a **capacity shortfall**, with no anticipation, i.e., that was not known to be happening in advance, at the airports where the detected loss occurs. The capacity shortfall is the reverse of the **airport hourly throughput capacity** increase of 5% proposed in previous section 3.3.3.

Besides, the performance benefit associated to the improved arrival punctuality of arrival flights is lost, so the tool customisation must also address the associated increase in primary delays related to arrival punctuality linked to TMA manoeuvres, by reversing the reduction in **parameter a1** described in section 3.3.3 for all incoming flights to the airport during the period of time of ASPA detected loss.

Additionally to the simulation of the failure approach through ATM-NEMMO features, it can be considered the impact of ASPA detected loss on the quantification of CATS diagrams. From a failure perspective, it is necessary to talk about the potential loss of separation linked to the loss of ASPA function. The associated loss of ASPA instructions means going back to normal operation modes, with the corresponding increase in workload for the controller, who needs to vector the aircraft. Besides, if the aircraft loss the capacity of adapting the speed to the position of the Target Aircraft (partial loss of ASPA capability), there is an increased risk of loss of separation.

3.4 ATSAW-ITP Safety Enhancement System

Automatic Dependent Surveillance Broadcast (ADS-B) is a system for communications between aircraft, and also between aircraft and ground. Both are vital in ensuring safe flights and efficiency in terms of fuel use, time and emissions. ADS-B is designed to ease Air Traffic Control (ATC) as the number of approaches grows, enhancing safety and increasing airport capacity. In the air, the information provided by ADS-B enhances the pilots' traffic awareness, allowing more optimal flight levels leading to fuel savings. ADS-B IN provides automated aircraft parameter transmission between aircraft themselves.

The Airbus approach to ADS-B IN is named the Air Traffic Situational Awareness (ATSAW) which enables the reception of ADS-B information from other aircraft in the vicinity [11]. ATSAW (Airborne Traffic Situation Awareness) is an on-board application providing information about ADS-B traffic to improve situational awareness. ATSAW consists of 4 applications: AIRB (Airborne), ITP (In-trail procedure), VSA (Visual Separation on Approach), and SURF (Airport Surface).

3.4.1 Impact on SESAR KPAs

ATSAW In Trail Procedure enables the flight crew to change flight levels more frequently to reach optimum flight levels or to exit areas of turbulence. This enhancement can allow on board surveillance by flight crew to determine if optimum flight levels can be reached. Based on calculations the function indicates if and when a FL change is possible based on the ADS-B information from the aircraft around. With ITP the flight crew can calculate the feasibility of a request for a certain FL at a time.

Thanks to enabling flying at the optimum flight level, the system is predicted to have a positive impact on **Efficiency**, helping to improve the number of flights with block to block time as planned and to reach the 2020 target of having 95% flights as planned. Other leg of the same impact is the reduction of the average block to block time extension of the flights with time longer than planned, with a SESAR 2020 target of average block-to-block time extension less than 10 minutes.

3.4.2 Expected Generic Impact on Safety

The function increases flight safety by providing a more intuitive display of surrounding aircraft, while also allowing pilots to better plan for oceanic flight level changes to reduce fuel burn – resulting in significant cost savings [11].An operational evaluation of the closely related ADS-B ITP performed by the FAA showed in 2011 that these fuel savings can be a reality [18].

The display of surrounding traffic position in the cockpit provides the flight crews with an "enhanced traffic situational awareness", irrespective of visual conditions, which improves safety of flight and efficiency of air traffic control. It is expected that this is translated into a reduction on the rate of mid-air collisions.

In all airspace, the flight crews will be better able to detect an unsafe situation. This leads to a reduced probability of flight crew errors in separation or ACAS response. The ATSAW-ITP also supports flight crew in planning and workload management, and intra-cockpit communication.

The impact is also for ATCOs:

- Slight positive effect on reduced demand on providing control information;
- Allow controller to call traffic earlier than normal;
- Moderate positive effect on reduced communications (less pilot requests on the traffic);

- Reduced uncertainties related to visual acquisition.

On the other hand, new safety hazards linked to ATSAW-ITP operation should be taken into account, such as possible unauthorised early avoidance manoeuvres by flight crew, possible over-reliance leading to reduction in visual awareness, confusion caused by mixed fleet equipage or pilot hesitation over controller's instruction.

3.4.3 Success Approach: Input Parameters to ATM-NEMMO linked to ATSAW-ITP Operation

The envisaged impact of ATSAW-ITP on SESAR Key Performance Areas, as discussed in previous sections, can be summarised as follows:

- General positive impact on Efficiency, in the form of reduced **block-to-block flight duration.**

The link with ATM-NEMMO input parameters is particularised below.

Reduced block-to-block flight duration.

Maximum variability in flight duration – is the % of increase or decrease in flight duration that can be expected for all flights due to en-route variability related to wind, weather conditions, etc.

To account for expected benefits of ATSAW-ITP in terms of flight duration, this parameter will set as an absolute allowed maximum change in flight duration of 10 minutes, maintaining also the percentage variation divided by two. Additionally, and taking into account the expected target fulfilment of 95% of flights having the planned ground-to-ground duration, as discussed in section 3.4.1, the parameter will apply in a probabilistic manner only to 5% of all IFR daily flights.

3.4.4 Failure Approach: Detected loss of ATSAW-ITP

The loss of the functionalities associated to the ATSAW-ITP has as direct impact a loss of en-route flight efficiency for affected flights. This is translated into worst compliance of planned trajectories and target times.

The approach for simulating this is to reverse the efficiency benefits discussed in previous section 3.4.3 for those flights suffering a detected loss of the system. Regarding the percentage of flights losing the ATSAW during a certain period or the totality of the en-route phase, its quantification is related to the failure rate of the system. Similarly to the discussion in section 3.2.4, the definition of a failure rate is leaved to the safety expert using the model. Again, it could be the case for ATSAW-ITP that the failure rate is low enough as to be negligible in terms of number of failures in a day of operation. In that case, the recommended use of ATM-NEMMO to simulate a detected loss of the system is the customisation for a simulation of longer periods of time, using the adequate traffic samples.

On the other hand, the impact of ATSAW-ITP detected loss on the quantification of CATS diagrams is linked to the following discussion. ATSAW-ITP enables the aircraft to reduce the standard separation (due to increase of pilot situational awareness), and therefore it allows to perform more flight level changes, optimizing flight level, In the case of loss of ATSAW-ITP, the pilot could not perform the level changes., impacting in terms of higher fuel consumption and possibly delays on the arrival time that could be linked to more time pressure for pilots, increased distress and, eventually, to arrival overloads (and increased ATCO workload) due to worst planning compliance.

4 Summary of Assumptions

The following assumptions apply in general to the simulation study on Global Safety Impact using a mesoscopic network model, and in particular to the example analysing the A-SMGCS Safety Enhancement System.

[ASU-1] The overall safety level of the total aviation system is impacted by the degree of amplification and propagation of uncertainties throughout the ATM system. Degraded situations with high congestion and large delays with long recovery times have an impact on Air Traffic Management aspects, such as controller workload, that at their turn are factors used to assess the probability of occurrence of safety events in the pathway of incidents.

[ASU-2] For the evaluation, through simulation, of the impact of a particular Safety Enhancement System (SEnS) on network-global performance, it is adequately representative the implicit simulation of the implementation of the SEnS, through the simulation of the efficiency/ predictability performance enhancements linked to it.

[ASU-3] The SESAR concept will create sufficient terminal area and en-route capacity so that it is no longer a constraint in normal operations. Free routing is assumed to be in place for most connections between airports, and thus airports are linked by the shortest routes.

[ASU-4] Each airport is characterized by its maximum capacity, in number of movements per hour. The constraining factors of this maximum capacity are runway throughput and TMA capacity.

[ASU-5] The more representative measure of the degree of amplification and propagation of uncertainties in the air transport network is the reactionary delay performance metric within the Predictability Key Performance Area.

[ASU-6] Global performance of the ATM system in the area of Capacity has an impact on the network overall safety level. In particular, the occurrence of airport throughput overloads is linked to safety degradation, due to increased ATCO workload and its influence on human errors.

[ASU-7] The implementation of A-SMGCS at an airport means a general positive impact on flight efficiency and predictability for all flights departing from/ arriving to the airport that is materialised in the form of reduced variability of taxi-time and a general reduction of taxi-time.

[ASU-8] At an airport where A-SMGCS is implemented, when an aircraft deviates from planned taxi-time above a certain threshold, there is a negative chain reaction impacting the whole queue of taxiing-out/ in aircraft at the airport, being this in the form of increased taxi-times for all aircraft during a period of time at least equal to the average taxi-out/ taxi-in time of the airport.

[ASU-9] The operation of A-SMGCS at an airport provides in average 20% reduction of total taxi-time for all aircraft departing from/ arriving to the airport.

[ASU-10] The operation of A-SMGCS at an airport provides in average a reduction of taxi-time variability that is particularised in a reduction by factor of two of the probability that a primary delay of 5-15 minutes occurs at the airport.

[ASU-11] The use of A-SMGCS may provide for maintaining higher levels of traffic during low visibility operations, thus minimising the negative capacity impact of such operational conditions.

[ASU-12] The generalised operation based on the use of BTV system means a general positive impact on predictability, in the form of better improved arrival punctuality and capacity, in the form of reduced Runway Occupancy Time.

[ASU-13] A reduced ROT is generalised in all airports in the network due to the presence of better equipped BTV aircraft in a high percentage. This is directly translated into an increase in runway capacity at airports, and given that runway capacity is considered the main limiting factor for airport capacity (see [ASU-4]), it is assumed that a reduced ROT in all airports can be simulated as a general increase in airport hourly throughput capacity of 5% (in the case of single-runway airports) and 15% (multiple-runway airports).

[ASU-14] The generalised operation based on the use of ASPA-IN-S&M means a general positive impact on predictability, in the form of better improved arrival punctuality and capacity, in the form of reduced Runway Occupancy Time.

[ASU-15] The improvement of arrival punctuality given by the implementation of ASPA-IN-S&M is translated into a reduction of 50% of the probability that a primary delay of 16-30 minutes occurs at the airport. It is assumed that primary delays related to arrival punctuality linked to TMA manoeuvres fall within the 16-30 minutes length range.

[ASU-16] An improved runway throughput is generalised in all airports in the network due to better approach sequencing linked to the operation of ASPA-IN-S&M. This is directly translated into an increase in runway capacity at airports, and given that runway capacity is considered the main limiting factor for airport capacity (see [ASU-4]), it is assumed that an improved runway throughput in all airports can be simulated as a general increase in airport hourly throughput capacity of 5%.

[ASU-17] The generalised operation based on the use of ATSAW-ITP means a general positive impact on efficiency, in the form of reduced block-to-block flight duration.

[ASU-18] Expected benefits of ATSAW-ITP in terms of flight duration are an absolute allowed maximum change of 10 minutes, and a 50% reduction on its percentage variation. It is expected that 95% of IFR flights have the planned ground-to-ground duration.

5 Modelling Scenarios

5.1 Baseline Scenarios

As introduced in section 2.3.4, baseline scenarios are used as baseline for the simulations. They intend to represent a situation where none of the Safety Enhancement Systems under study are in place. The baseline in ATM-NEMMO is an unspecific SESAR environment where certain future improvements apply. In particular, the model approach does not consider airspace structures and their associated management. It is assumed that "*the SESAR concept will create sufficient terminal area and en-route capacity so that it is no longer a constraint in normal operations*" (assumption coming from the SESAR initial ConOps).

Free routing is assumed to be in place for most connections between airports, and thus airports are linked by the shortest routes. Highly congested areas are considered as additional nodes of the network with capacity restrictions.

The baseline scenarios are created through certain network characteristics and traffic customization. Additionally to the representation of nominal conditions, baseline scenarios also cover changes in the traffic volume and the application of external disturbances causing capacity shortfalls at airports and HDAs. The aim is to simulate also certain changes until arriving gradually at an extreme situation. This facilitates the analysis of the system behaviour and the potential safety benefits of Safety Enhancement Systems also under critical conditions of operation.

A disturbance is an event which produces variations from the planned operation of the Air Transport processes or elements. External disturbances are produced by an element which is not part of the Air Transport network.

It is understood that the behaviour of the air transport system in terms of safety in special situations differs from the nominal behaviour. It is expected that under certain circumstances increased safety measures are put in place. The use of external disturbances in the present study aims at analysing the contribution to the safety risk level of Safety Enhancement Systems under critical conditions, where the impact of chosen events on predictability/ efficiency and capacity is translated into local increased probabilities of safety incidents. The results of the ATM-NEMMO/ CATS analysis could be an input for safety practitioners to the analysis of the potential hot spots where countermeasures might apply.

ATM-NEMMO has implemented two different categories of external disturbances based on Local phenomena and Geopolitical causes. The unexpected events considered for the modelling scenarios are as follows:

<u>Local phenomena:</u>

Storm affects Holland and Belgium (A)**:** 5 airports are impacted, and at network level a 30% capacity shortfall is detected from 9.00 am to 12 am.

Ash cloud in Iceland (B): based on the Grimsvötn eruption in May 2011. Its impact was more limited than that of Eyjafjallajökull in April 2010, but still it provoked severe capacity shortfalls in certain zones of Europe (see Figure 9 below).

According to the Volcanic Ash Advisory Centre (VAAC) in London, areas of ash concentration were over the north of Germany and no flights were accepted into Bremen and Hamburg. As a result approximately 450 flights were cancelled in German airspace, mainly affecting airports in Bremen, Hamburg and Berlin. On a normal day, these airports would expect around 120, 480 and 530 flights respectively.

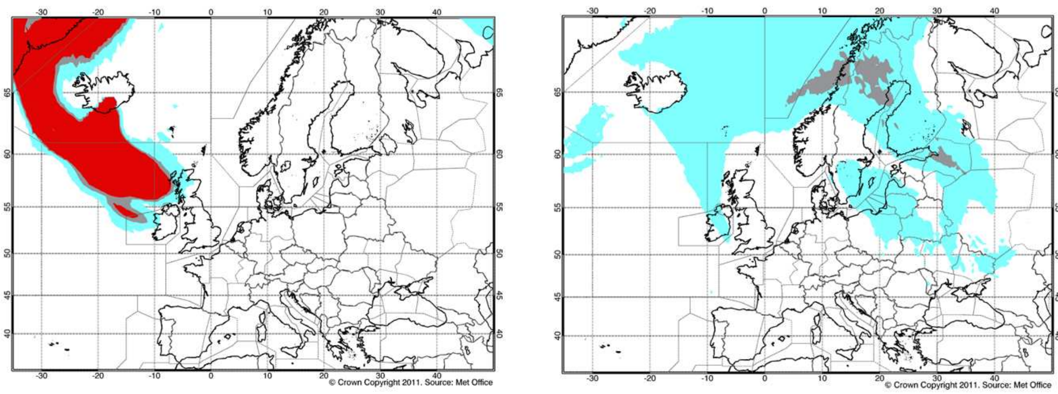

Figure 9 Volcanic ash concentration charts for Grimsvötn ash plume on 26 May 2011

<u>Geopolitical phenomena:</u>

London Heathrow security check performed more in-depth (C): An airport is impacted and all departing flights have 30 minutes of delay during the whole day.

French Airspace Controllers on strike (D): 3 airports are impacted, 10% of the departing flights are cancelled and the rest have 40 minutes of delay.

5.2 Specific Scenarios

Specific scenarios are defined according to the Safety Enhancement Systems detailed in section 3. As introduced in section 2.3.4 and developed in section 3, for the analysis of the impact on overall safety level of each Safety Enhancement System two scenarios are considered: success approach and failure approach. In order to obtain the safety risk picture associated to any of them, the simulation results of the scenario must be compared to the corresponding baseline scenario. An example is shown in next table.

Scenario	Δ PI	Associated safety risk variation
Success scenario SEnS 1 + External disturbance B	+z%	+x% in ESD-5*
Baseline scenario + External disturbance B		

Table 5 Comparative Variation of Safety Risk Associated to Safety Enhancement

* For more details see next section 6.

Besides, the particular scenarios considered can represent an inhomogeneous application of the Safety Enhancement Systems throughout the network, for those systems aiming at improved operations at airports, with highly safety robust airports and other airports with increased uncertainty in operations. For the A-SMGCS, for instance, it is highly likely that the implementation of level 4 is limited to heavy airports and medium airports with complex layouts or frequent low visibility conditions, whereas normal medium and light airports are not so likely to invest in this type of system.

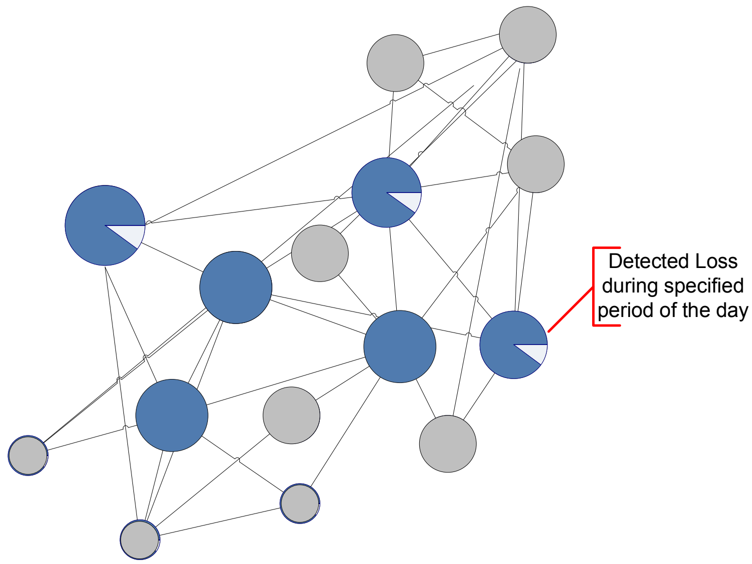

Figure 10 Representation of Specific Scenario for Inhomogeneous Application of System and Periods of Detected Loss

For the failure scenarios consisting on detected loss of a Safety Enhancement System, also inhomogeneous applications are possible, with detected loss only at certain airports where the system in implemented and during different periods of time.

A given specific scenario is therefore defined by:

- Baseline scenario;
- External disturbance (if any);
- Safety Enhancement System implemented;
- Type of Implementation:

	Implementation		
Approach	Network-wide	Airport	Cluster of airports
Success Approach			X
Failure Approach			X

Table 6 Specific Scenario X Characterisation

- For the Failure Approach, definition of period of detected loss particularised at the level of network, cluster or airport.

6 Type of Simulation Results

The results, in terms of overall safety level, can then be obtained at:

- Network level, using the variations of the global PIs (see section 2.3.3) as homogenous input to the Fault Trees in the CATS module;
- Airport level, using the variations of the related local PIs at the specific airport;
- Cluster level, where PIs can be defined at a semi-global level, integrating only measures from a pre-defined set of airports, that can be, for example, those where an inhomogeneous implementation of a given Safety Enhancement System.

The results present the safety risk picture in terms of probability of occurrence of safety accident or incident for each of the seven end-states considered in ASCOS WP3.2 [12]:

- Runway excursion;
- Collision with ground;
- In flight break-up;
- Collision in mid-air;
- Collision on runway;
- Collision with ground;
- Collision on taxiway or apron.

For each of them, calculated variation with regard to the baseline situation is shown per each of the ESDs in which the end-state is used. A graphical representation of this overall safety level associated to a given Specific Scenario is shown in next figure.

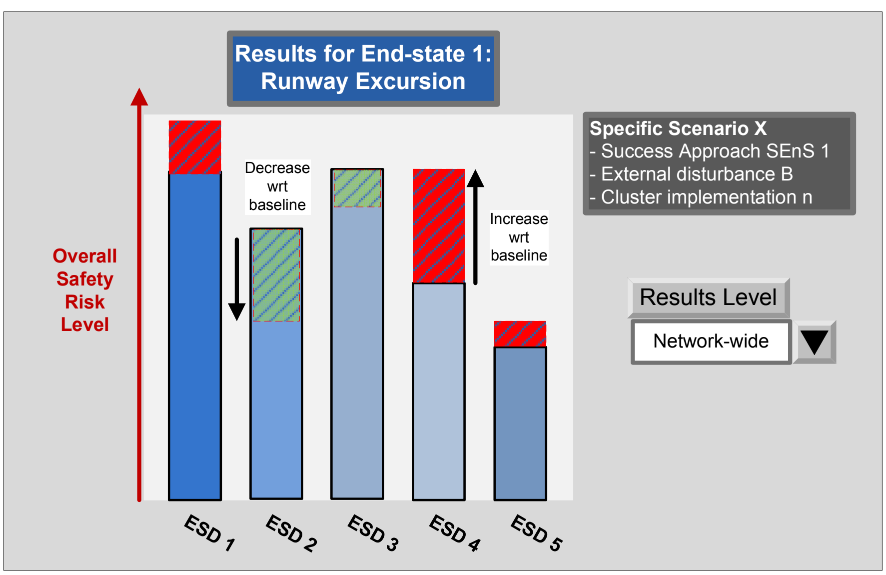

Figure 11 Overall Safety Level for Specific Scenario and End-State

7 Conclusions and recommendations

The consideration of flight delays and other performance measures of the ATM system for the estimation of the total aviation system safety risks is a domain of study that is gaining attention. Long term and innovative research approaches are seeking to deepen into the ATM influences on safety risk, and in particular to explore how to better understand the ATM network behaviour and its retrofit in safety performance. SESAR network on "Mastering complex system safely", introduced at the beginning of this document, is putting effort in this line of investigation. Modelling and simulation techniques are proposed to be used for trying to refine the estimation of safety risks by incorporating ATM network performance related factors, such as efficiency, predictability or uncertainty propagation.

The relationship between flight delays and safety in airline maintenance has been previously considered by safety practitioners. A wider consideration of the relation between delays and civil aviation safety risk is analysed in a paper focussed in the Chinese air transport network [19]. This relation being complex, the article explores how they can be linked to propagation and superposition of civil aviation safety risk through the use of Bayesian Networks as modelling tool. The test-case for some airlines in China demonstrates the effectiveness and correctness of the proposed method.

The present document is a theoretical approach to the same issue, proposing the integration of traditional safety causal models into an innovative modelling and simulation tool with capacity to capture network performance and propagation of ATM related uncertainties. Sharing this discussion with the ATM and safety community will bring useful feedback on the way forward. And of course, implementing the proposed approach and testing representative cases will reveal strengths and weaknesses of the method as well as provide more insight into the intricacies of managing the complex air transport network and ensuring that safety risks are minimised.

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Appendix A ATM NEMMO Technical Specifications

Appendix A.1 General Flow Diagrams

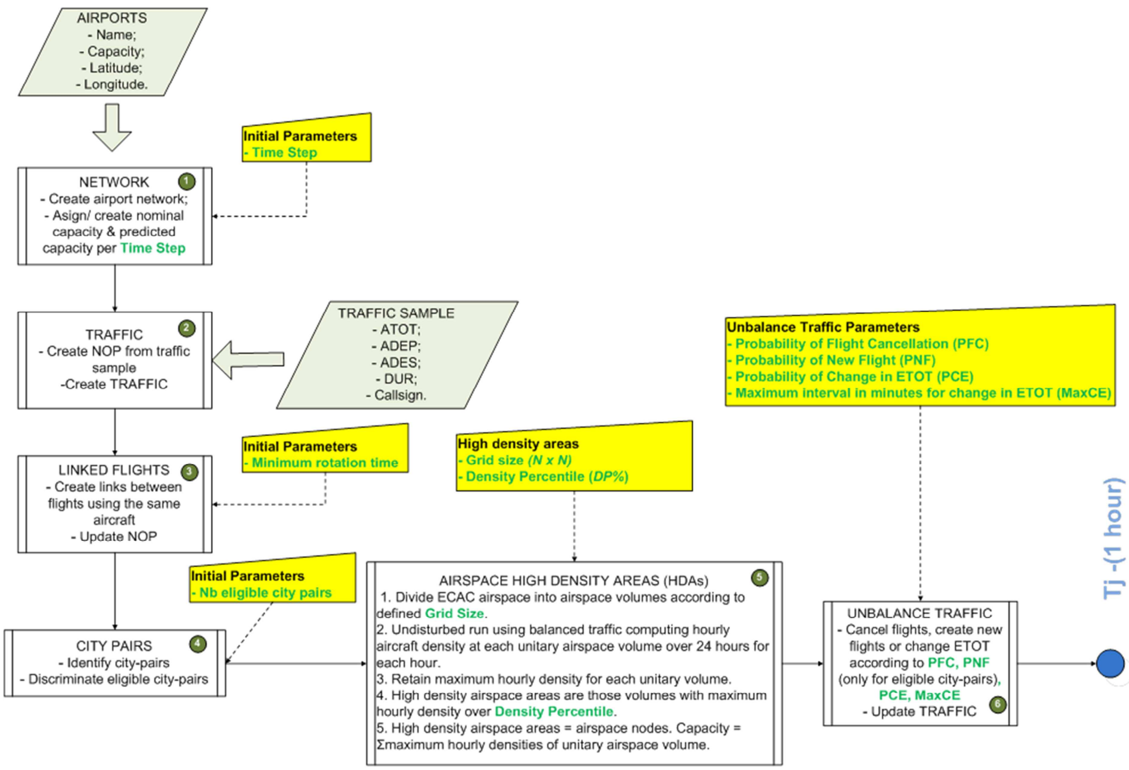

Figure 12 Process Diagram I

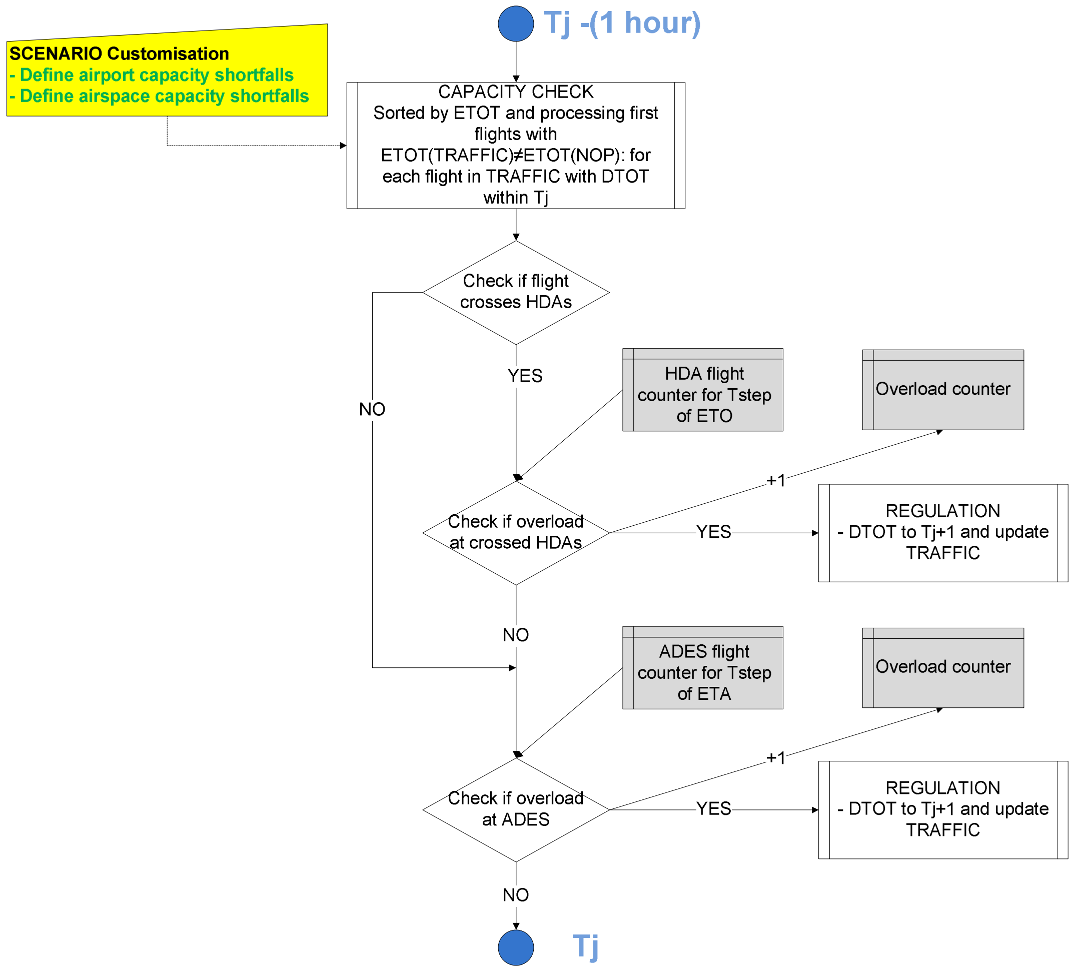

Figure 13 Process Diagram II

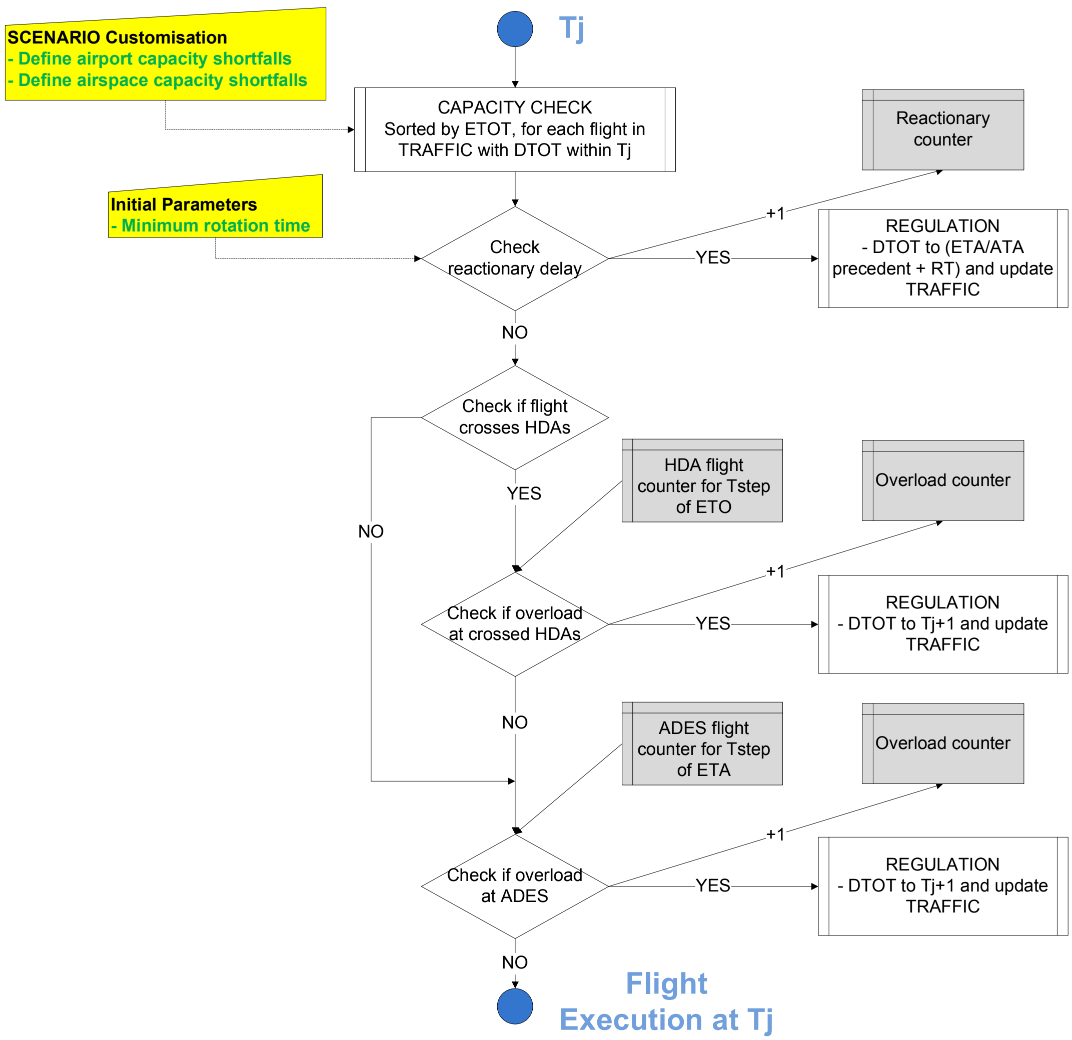

Figure 14 Process Diagram III

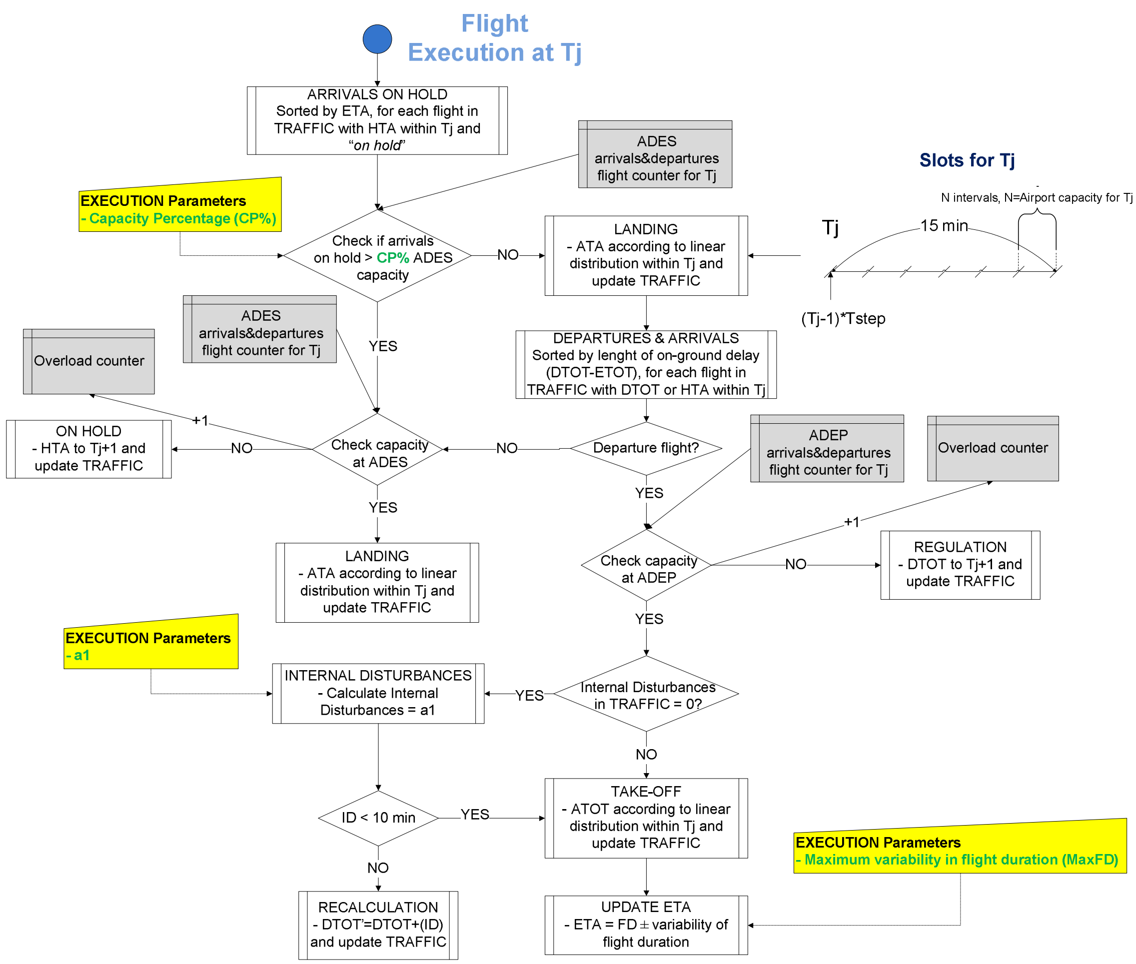

Figure 15 Process Diagram IV

Appendix A.2 Process Flow

Appendix A.2.1 NETWORK

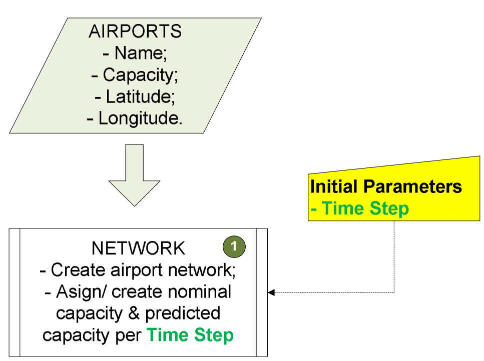

Figure 16 NETWORK Process

The NETWORK process create airport network from the input data "Airports" (see section A.3.1).

NETWORK includes: the main ECAC airports included in "Airports" + one node OTHER, which integrate *departures from/ arrivals to* airports not included in main ECAC set of airports (secondary airports).

Position of node OTHER is defined as follows:

- OTHER groups all secondary and small airports within ECAC geographical area and it is located at Latitude 54, Longitude -20 (see figure below).

Figure 17 Location of Node OTHER

Secondary and small airports integrated in OTHER are all those not already included in the main list and starting by the following ICAO letters: E, L, B and (UD, UK, UB, UG & UM). The criterion for the selection of ICAO codes to be included under OTHER is geographical, which means that not all airports grouped in OTHER belong to ECAC area.

The parameter **Time Step** indicates, in minutes, the time interval used by the model for executing the algorithms.

- Nominal and predicted capacity are assigned for each airport, where **nominal capacity** is initially equalled to the data hourly capacity in "Airports" divided by the number of Time Steps in an hour (e.g. 4 for a Time Step of 15 minutes) except for the node OTHER, for which capacity is set at a sufficiently high value (100.000 movements/ Time Step). Nominal capacity of each airport is changed during the simulation to reflect the **real capacity** of the airport at each Time Step, which can differ from the nominal data in "Airports" in the case of a capacity shortfall in the airport.

- **Predicted capacity** is used to indicate whether the information available in the network about the real capacity of the airport at a given Time Step is equal or not to the real capacity of the airport at that Time Step. In case a capacity shortfall is "visible" in the network, predicted capacity will be equal to nominal (real) capacity. In other case, predicted and nominal capacity might have different values.

Appendix A.2.2 TRAFFIC

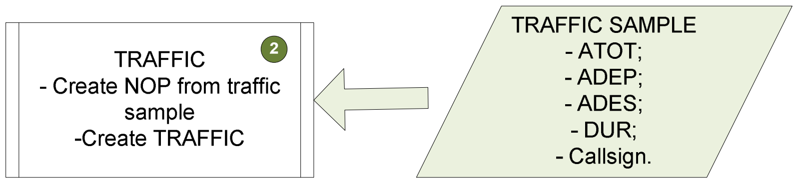

Figure 18 TRAFFIC Process

From input data in "Traffic sample" (see section A.3.2), the TRAFFIC process creates two structures:

- **NOP**, in which ATOT, ADEP, ADES and FD data from "Traffic sample" are copied. If ADES/ADEP are not within the main set of airports in "Airports", then the process check for coincidences between the first letter of the airport ICAO code and any of the AREA nodes defined in "Airports" (see section A.3.1). In case no coincidence is found (i.e., for all the rest of airports) NOP assign ADEP/ADES to node OTHER (see section A.2.1). ETOT (Estimated Take-Off Time) of each flight in NOP is fed from the ATOT data. Additionally, NOP structure contains the column "Precedent (linked) flight" to indicate if the flight is using the same aircraft than a previous flight in NOP (see section A.2.3).

NOP				
1. ADEP	2. ADES	3. ETOT	4. FD	5. Precedent (linked) flight

Figure 19 NOP Structure (in grey data from "Traffic sample")

- **TRAFFIC**, which is used as a living structure that reflects, at any time during the simulation, the status of each flight. It is composed of the following columns for each flight:

    1. Pointer to NOP structure;
    2. ETOT: initially set as the same value than ETOT in NOP;
    3. DTOT (Delayed Take-Off Time): initially equal to ETOT and used to indicate that a flight has been delayed on-ground, in which case DTOT is not equal to ETOT;
    4. ID (Internal Disturbances): used to account for delays due to sources of uncertainty during rotation;
    5. ATOT (Actual Take-Off Time): registers the actual take-off time;
    6. ETA (Estimated Time of Arrival): equal to DTOT + FD in NOP when a flight has not taken-off yet. It is also updated once the flight took-off to reflect the variability in Flight Duration – FD (see section A.2.9);

7. HTA (Holding Time of Arrival): equal to ETA unless the flight is on-hold at arrival airport due to capacity restrictions, in which case it reflects the expected time of arrival taking into account the time on-hold;
8. ATA (Actual Time of Arrival): registers the actual time of arrival;
9. Callsign;
10. Other fields as necessary for the implementation of local rules.

TRAFFIC								
1. NOP Pointer	2. ETOT	3. DTOT	4. ID	5. ATOT	6. ETA	7. HTA	8. ATA	9. Callsign

Figure 20 TRAFFIC Structure

Appendix A.2.3 LINKED FLIGHTS

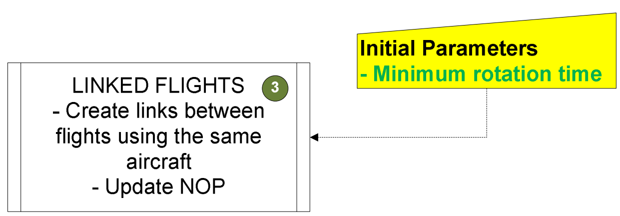

Figure 21 LINKED FLIGHTS Process

In case traffic sample does not include aircraft registration, which is the case when using as input a traffic sample coming from traffic growth scenario, an algorithm is used to create the links for flights within the same airline taking into account a minimum stopover time. Information of links created using the algorithm described below is updated in NOP.

Flight Linking Algorithm

1. For every flight, origin and destination are checked to identify circuit flights, where origin and destination are the same. These flights are not linked with any other flight (as they are typically test flights, training, etc.)
2. For each one of the rest of flights:
   a. Destination airport is compared with departure airport of all flights of the same aircraft operator and coincidences are retained;

b. For coincidences, the first flight with ETOT at least **Minimum Rotation Time** minutes after ETA of the flight being compared is marked as subsequent flight (using the same aircraft) of the flight being compared. The process initially applies a standard Minimum Rotation Time for all flights, though this could be customised per type of aircraft, type of airline, etc.

Appendix A.2.4 CITY PAIRS

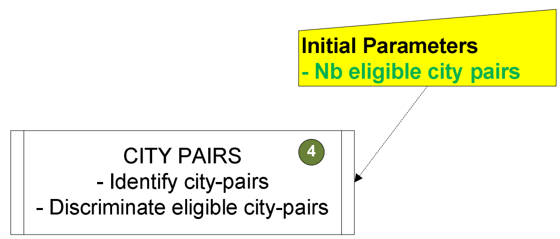

Figure 22 CITY PAIRS Process

This process identifies city-pairs in NOP, i.e. airports that have flights connecting them. From all city-pairs, the model discriminates those highly interconnected, which are called “eligible city-pairs” and used afterwards in the process of unbalancing traffic (see section A.2.6).

All city pairs are sorted by number of flights between them along the day. The model retains the first N city-pairs in the list, being N equal to the parameter **Number of eligible city-pairs**. The value of the parameter should correspond to the number of busiest city-pairs in Europe.

Appendix A.2.5 AIRSPACE HIGH DENSITY AREAS

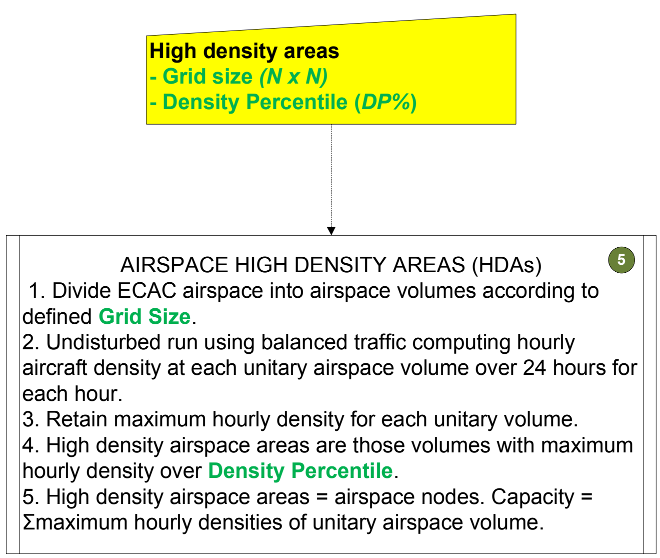

Figure 23 AIRSPACE HIGH DENSITY AREAS Process

The HDA process detects airspace areas which present some hour(s) over the day with “high traffic density”. To perform this, the process executes the following:

1. ECAC airspace is defined between (lat1,lon1) and (lat2,lon2) being lat1 the latitude of the southern airport in the main set in “Airports” (see section A.3.1), lon1 the longitude of the western airport, lon2 the longitude of the eastern airport and lat2 the latitude of the northern one. The airspace is divided into a grid of equal squares. The parameter **Grid Size** determines the number of equal squares (unitary airspace volumes) of the grid. For example, if the parameter is 100 x 100, the airspace is divided into 10.000 squares of equal size.

2. An undisturbed run, meaning that there is no uncertainty and all flights are executed according to planned schedule, is used to compute the hourly aircraft density at each unitary airspace volume for each time interval of 60 minutes along the day.

   For this run, flights with origin or destination to node OTHER or nodes type AREA are not taken into account, given that the position of these nodes are fictitious (see section A.2.1 and A.3.1) and trajectories to them could introduce erroneous data for the computation of airspace congestion.
   To establish the position of each aircraft at each hourly time interval, the route between departure and arrival airports is considered as the geodesic trajectory between the position of arrival airport and the position of departure airport, and the aircraft is considered to follow this trajectory with a constant speed such that time to complete the trajectory is equal to the duration of the flight in NOP.

3. For each unitary airspace volume, it is recorded the maximum hourly aircraft density of the day, independently of the hourly time interval when this maximum is reached.

4. The model retains as **high density airspace areas** all volumes with maximum hourly aircraft density over the **Density Percentile**, i.e. over the maximum hourly density that is higher than the maximum hourly density of the **DP%** of volumes.

Appendix A.2.6 UNBALANCE TRAFFIC

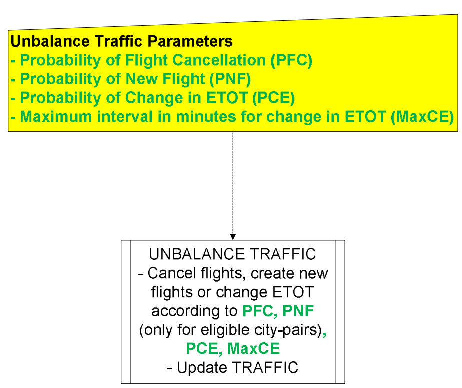

Figure 24 UNBALANCE TRAFFIC Process

Finally, before the day of operations, the model performs the process UNBALANCE TRAFFIC. The rationale for this process is that the traffic sample used as an input, being flown traffic, is balanced in terms of capacity and demand, which is not realistic for a traffic demand. The other reason to include this process is to reflect changes in schedule that occurs in the medium/short-term planning phases, i.e. before the day of operations or execution phase. These changes are motivated by increased availability of accurate weather predictions, traffic demand, ANSPs and airport capacities, etc. The changes considered here are particularised in flight cancellations, appearances of new flights and changes in ETOT. The consequence is an unbalanced traffic demand with regards to capacity as input for the execution phase, during which tactical DCB measures (such as ground delay, flight level capping or re-routings) are applied to adapt demand to the available capacity.

The process works as follows:

- Randomly eliminates **PFC%** of flights.
- Duplicate **PNF%** of flights of eligible city-pairs (see section A.2.4).
- Change ETOT of **PCE%** of flights in an interval (in minutes) of [-**MaxCE**/2,+**MaxCE**].

Appendix A.2.7 Departure CAPACITY CHECK Tj-(1 hour)

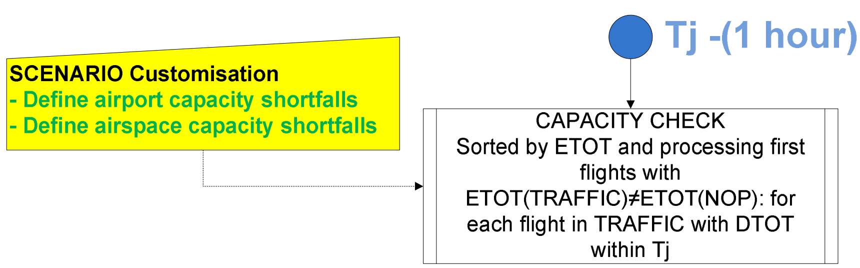

Figure 25 CAPACITY CHECK at Tj-1 hour (I)

At Tj-1 hour, the first capacity check for flights planned (in TRAFFIC) for departure within Tj is produced. The CAPACITY CHECK process checks that predicted capacity at destination airports and crossed HDAs is enough to respond to the planned demand of flights departing within Tj. The different checks performed lead to impose, in case of need, regulation in the form of on-ground delays.

All flights with DTOT (see TRAFFIC structure in section A.2.2) within Tj are sorted by planned departure time (DTOT) for the process to perform the checks. Flights that already suffered a change in ETOT in the course of UNBALANCE TRAFFIC process (see section A.2.6), so for which ETOT(TRAFFIC)≠ETOT(NOP), are **prioritised** and the last in being subject to regulation.

The parameters defined for airport and airspace capacity shortfalls are taken into account to update real and predicted capacity of airports and to introduce custom **additional HDAs with limited capacity.**

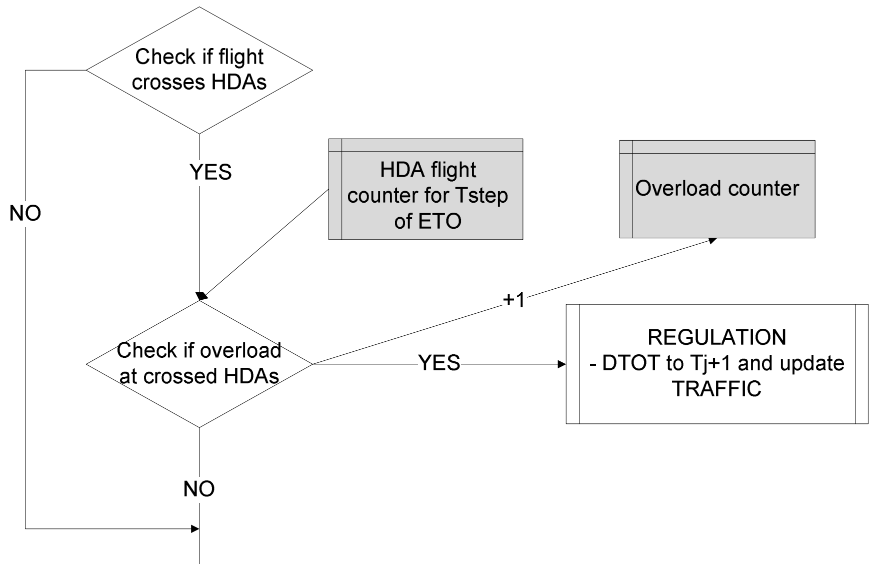

Figure 26 CAPACITY CHECK at Tj-1 hour (II)

For each flight and each HDA that it crosses the process compares the HDA predicted capacity with the number of simultaneous flights expected at the HDA at the Tstep following the entry of the flight in the HDA (ETO – Estimated Time Over). ETO is calculated assuming that trajectory is performed at a constant speed and taking into account DTOT and distance from departure airport to the HDA node or to the HDA limit (in case of custom HDAs defined through "airspace capacity shortfall" parameters).

If predicted capacity is expected to be exceeded for Tstep of ETO, an overload occurrence is registered for the HDA at the Tstep of ETO.

Then, flights are regulated imposing on-ground delay. Since the capacity check is performed first for flights with ETOT(TRAFFIC)≠ETOT(NOP) and in order of DTOT, then flights with ETOT(TRAFFIC)=ETOT(NOP) and with DTOT closer to the end of Tj are more likely to be subject to regulation. Before delaying on-ground, the process REGULATION checks if the flights subject to regulation (all flights over the HDA at Tstep of ETO) have already taken-off (it they have ATOT in TRAFFIC structure – see section A.2.2), in which case the regulation is obviously not applicable. For flights regulated, a new DTOT (DTOT') is assigned, set at the first minute of Tstep T(u+1) (being Tu the Tstep of DTOT of the flight being regulated).

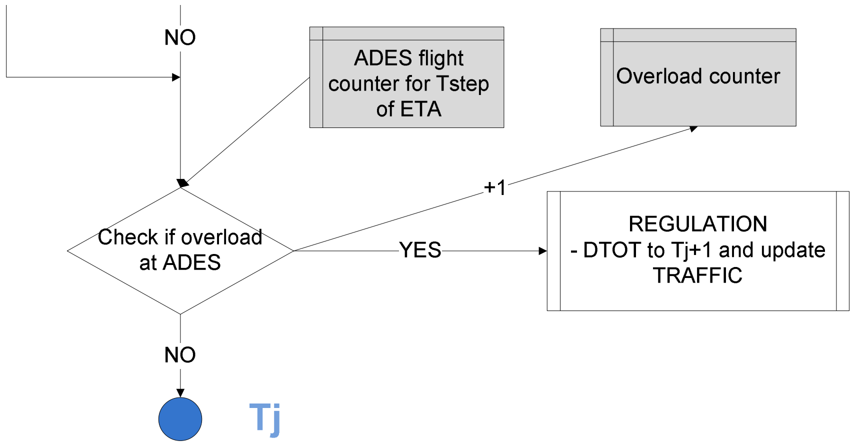

Figure 27 CAPACITY CHECK at Tj-1 hour (III)

If the flight being checked does not cross any HDA or no overload is expected for crossing it (so no regulation yet), then the process checks capacity at destination airport (ADES). Similarly to the process for checking capacity at crossed HDAs, ETA (Estimated Time of Arrival) is used to determine the Tstep for which capacity check at ADES must be performed.

If predicted capacity is expected to be exceeded for Tstep of ETA (because of arriving and departing flights to the airport), an overload occurrence is registered for ADES at the Tstep of ETA. Then, flights are regulated imposing on-ground delay. Before delaying on-ground, the process REGULATION checks if the flight has already taken-off (it has ATOT in TRAFFIC structure), in which case the regulation is obviously not applicable. For flights regulated, a new DTOT (DTOT') is assigned, set at the first minute of Tstep T(u+1) (being Tu the Tstep of DTOT of the flight being regulated).

Appendix A.2.8 Departure CAPACITY CHECK Tj

The departure CAPACITY CHECK performed at Tj (the Tstep of operation in the day of operation) is the final check to clear for take-off the flights planned for departure within Tj. The process is similar to that performed one hour in advance (see section A.2.7), including small differences that are highlighted here below.

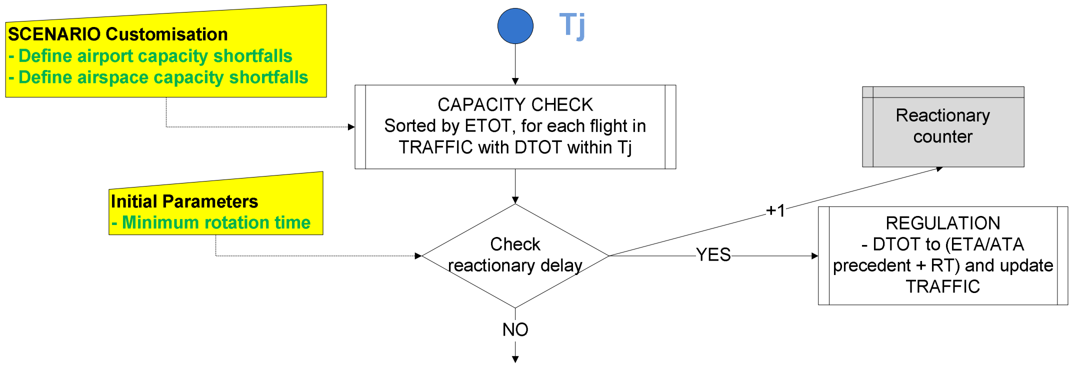

Figure 28 CAPACITY CHECK at Tj (I)

The first check performed, not performed yet in the check at Tj-1 hour, is if the precedent flight (if there is any – see section A.2.3) has already landed at the airport (ADES for precedent flight, and ADEP for departing flight). The process also checks that a **Minimum Rotation Time** has elapsed since landing.

If there is a reactionary delay, the flight is regulated imposing on-ground delay. DTOT of the flight is calculated as follows:

DTOT = ETA/ATA (precedent) + Minimum Rotation Time

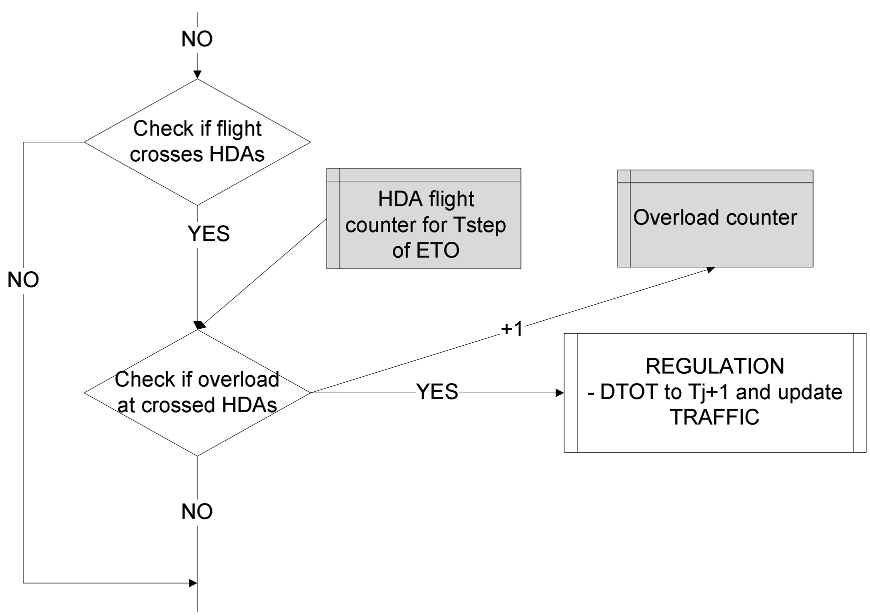

Figure 29 CAPACITY CHECK at Tj (II)

For each flight and each HDA that it crosses the process compares the HDA predicted capacity with the number of simultaneous flights expected at the HDA at the Tstep following the entry of the flight in the HDA (ETO – Estimated Time Over). ETO is calculated assuming that trajectory is performed at a constant speed and taking into account DTOT and distance from departure airport to the HDA node or to the HDA limit (in case of custom HDAs defined through "airspace capacity shortfall" parameters).

If predicted capacity is expected to be exceeded for Tstep of ETO, an overload occurrence is registered for the HDA at the Tstep of ETO.

Then, flights are regulated imposing on-ground delay. REGULATION checks, for all flights potentially subject to regulation, if the flight has already suffered a delay (DTOT≠ETOT) in which case the flight is not considered for regulation. The process also checks if the flights subject to regulation (all flights over the HDA at Tstep of ETO) have already taken-off (it they have ATOT in TRAFFIC structure – see section A.2.2), in which case the regulation is obviously not applicable. Finally, longer flights in terms of flight duration are regulated first, since it is assumed that longer flights can more easily recover from delay during en-route phase.

For flights regulated, a new DTOT (DTOT') is assigned, set at the first minute of Tstep T(u+1) (being Tu the Tstep of DTOT of the flight being regulated).

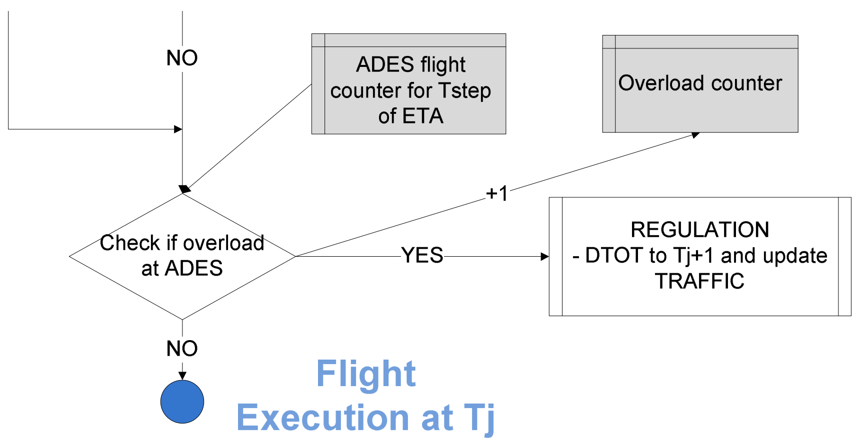

Figure 30 CAPACITY CHECK at Tj (III)

Finally, the process checks capacity at destination airport (ADES). ETA (Estimated Time of Arrival) is used to determine the Tstep for which capacity check at ADES must be performed.

If predicted capacity is expected to be exceeded for Tstep of ETA (because of arriving and departing flights to the airport), an overload occurrence is registered for ADES at the Tstep of ETA. Then, flights are regulated imposing on-ground delay. Before delaying on-ground, the process REGULATION checks if the flight has already taken-off (it has ATOT in TRAFFIC structure), in which case the regulation is obviously not applicable. REGULATION checks, for all flights potentially subject to regulation, if the flight has already suffered a delay (DTOT≠ETOT) in which case the flight is not considered for regulation. Finally, longer flights in terms of flight duration are regulated first, since it is assumed that longer flights can more easily recover from delay during en-route phase.

For flights regulated, a new DTOT (DTOT') is assigned, set at the first minute of Tstep T(u+1) (being Tu the Tstep of DTOT of the flight being regulated).

Appendix A.2.9 FLIGHT EXECUTION at Tj: Departures and Arrivals

Execution of flights at Tj starts processing first arrival flights on hold at ADES. The process lands all flights on hold by order of ETA (which given the modelling framework is equivalent of landing first flights that have been on hold for longer time). Up to **CP%** of ADES capacity is reserved for landing holdings.

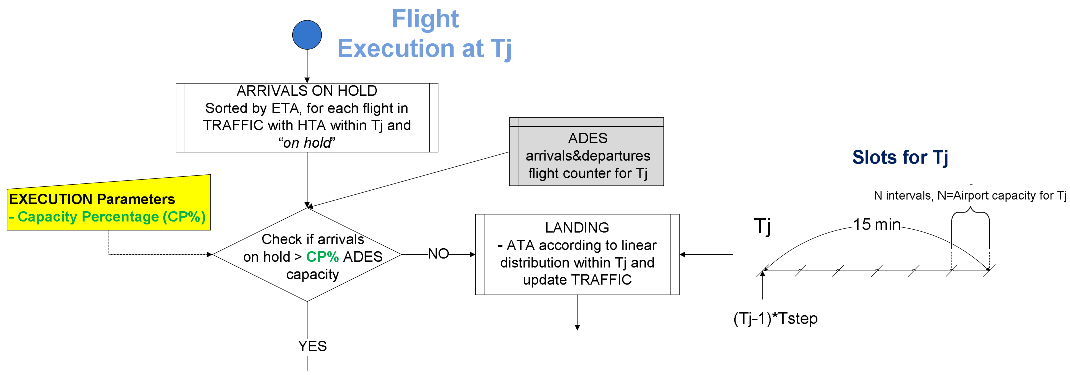

Figure 31 ARRIVALS ON HOLD at Tj

If there is enough capacity, ATA of flights are assigned following a linear distribution of slots within Tj: the interval (15 minutes) is divided into N equal slots being N the capacity in number of movements of ADES for Tj.

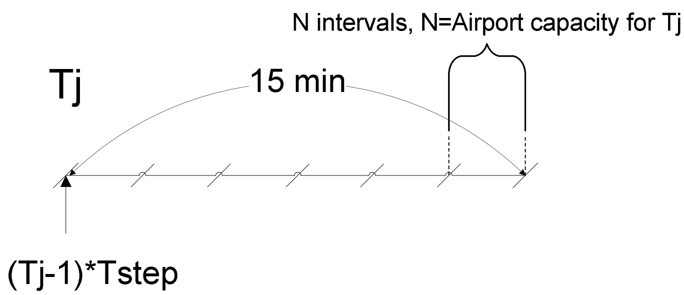

Figure 32 Linear distribution of slots within Tj

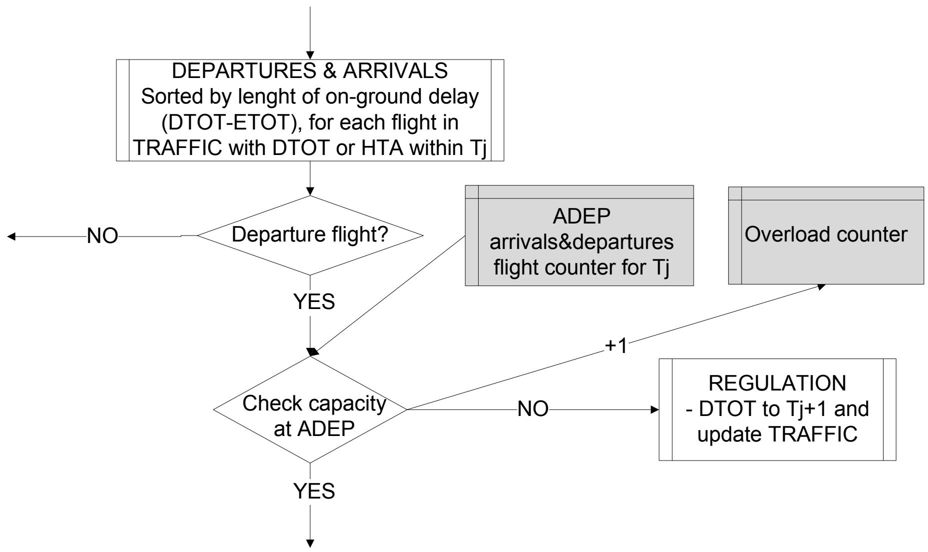

Figure 33 DEPARTURES at Tj (I)

Once all flights on hold at Tj have landed or all reserved capacities at ADES have been consumed, the following step processes all the rest of arrivals and departures within Tj. Flights are sorted by length of on-ground accumulated delay (DTOT-ETOT). If the flight is a departure and there is not enough capacity at ADEP, the flight is delayed on-ground: a new DTOT (DTOT') is assigned, set at the first minute of T(j+1). Otherwise, the flight is considered to have a slot time (CTOT – Calculated Take-Off Time) assigned. The slot is actually a period of time within which take-off has to take place: in Europe defined between −5 and + 10 minutes from CTOT. The aircraft is required to be at the runway, ready for departure at its CTOT.

At this point, of execution, **internal disturbances** are in place to account for uncertainty of duration of the rotation. Although the flight is scheduled within Tj and there is slot availability at Tj, it can occur that the flight is delayed on-ground due to causes internal to the airport (problems with handling, delays in de-boarding/ boarding, malfunctions of airport services, etc.) or due to delay produced during taxi-in (previous flight)/ taxi-out. The flight can miss its assigned slot if delay due to these causes exceeds 10 minutes (see Figure 34 and section A.3.3).

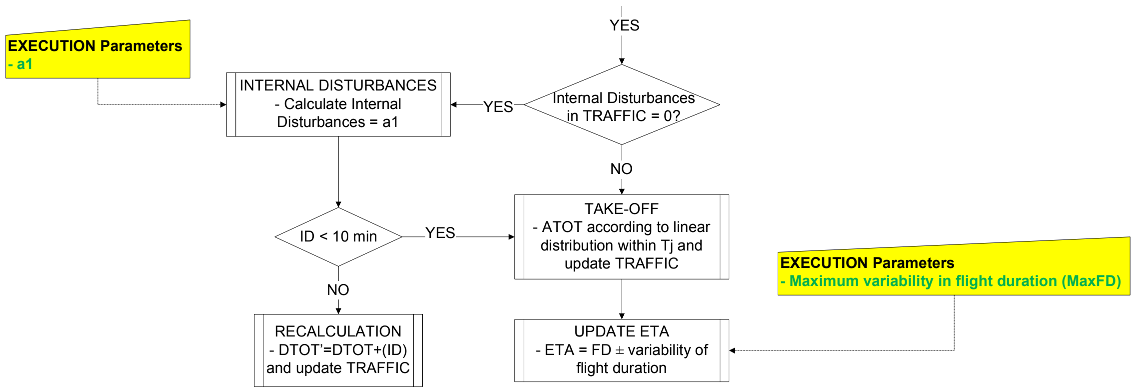

Figure 34 DEPARTURES at Tj (II)

The field ID in TRAFFIC (see section A.2.2) is used to store internal disturbances for each flight. If there is already a value in the field, it means that a stochastic variable has been already calculated for the flight taking into account the probability distribution corresponding to the parameter **a1** as described in section A.3.3. In that case, DTOT/ETOT is already reflecting any delay related to rotation and the slot that has been assigned according to this DTOT/ETOT will not be missed. So the flight takes-off and ATOT is assigned according to the linear distribution of slots within Tj depicted in Figure 32.

In case the field ID in TRAFFIC is empty, the process calculates a value for it based on the probability distribution of the parameter **a1** as described in section A.3.3. If the primary delay obtained is greater than 10 minutes, the slot is missed and a recalculation of slot (DTOT) takes place. The new DTOT' is calculated as DTOT+ID. In case ID is less than 10 minutes, it is considered that the slot will not be missed, so the flight takes-off and ATOT is assigned according to the linear distribution of slots within Tj depicted in Figure 32.

Finally, ETA of flights that have taken-off is calculated taking into account a maximum variability in flight duration of **MaxFD%**.

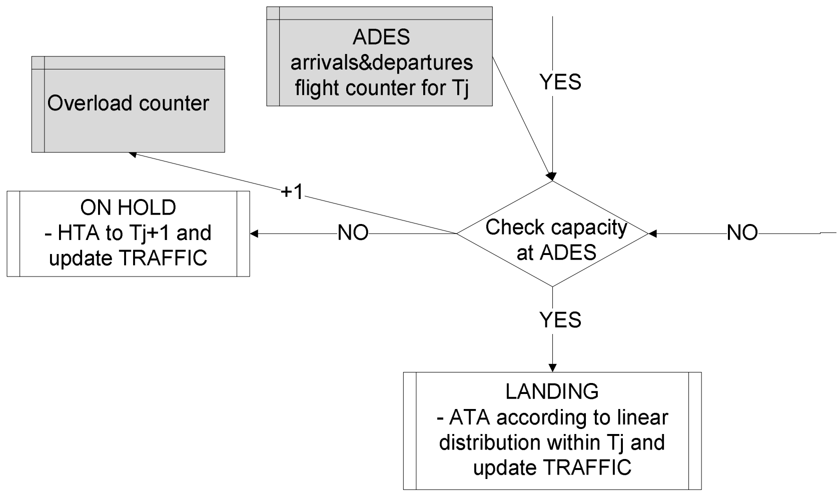

Figure 35 ARRIVALS at Tj

For arrivals, the process is similar. If there is enough capacity at ADES, flight is landed and ATA is assigned according to the linear distribution. Otherwise, flight is held until the first minute of T(j+1).

Appendix A.3 Inputs

Appendix A.3.1 Airports

The set of airports included in input data "Airports" is defined using the traffic sample (see section A.3.2) by selecting the main ECAC airports in terms of traffic: those handling 90% of traffic in the selected traffic sample.

Data for each airport in the set are:

- Name in ICAO code;
- Capacity, in number of flights per hour;
- Latitude;
- Longitude.

Additionally, the list is extended with **five nodes** called AREA nodes that integrate *departures from/ arrivals to* airports outside ECAC grouped by geographical areas:

- AREA 1 groups all airports with ICAO code starting with letters G, D, H and F.

Figure 36 ICAO regions – first letter code

- AREA 2 O, V, W, A, N and Y.
- AREA 3 U (except UD, UK, UB, UG & UM), Z, and R.
- AREA 4 C, K and P.
- AREA 5 M, T and S.

These AREA nodes are points in the limits of the grid that represent the ECAC area. For defining the exact location of these nodes, the intersections between the grid limits and five representative flows, going from the main European airports to representative airports in each of the areas, have been calculated. The five flows considered are:

- LFPG (Paris- Charles de Gaulle) to FAJS (Johannesburg –OR Tambo) for AREA 1 node.
- EDDF (Frankfurt) to YSSY (Sydney –Kingsford Smith) for AREA 2 node.
- EHAM (Amsterdam- Schiphol) to RJAA (Tokyo-Narita) for AREA 3 node.
- EGLL (London-Heathrow) to KJFK (New York- JFK) for AREA 4 node.
- LEMD (Madrid – Barajas) to SABA (Buenos Aires-Ezeiza) for AREA 5 node.

For the nodes AREA type, capacity is set at a sufficiently high value (400.000 movements/ hour).

Appendix A.3.2 Traffic sample

The one-day ECAC traffic sample used as input contains the following data for each flight:

- Callsign;
- ATOT;
- AOBT;

- Adep;
- Ades;
- Duration;
- Registration;
- Equipment;
- Type of flight (regular/ charter);
- Type of aircraft.

Appendix A.3.3 Internal Disturbances (Uncertainty)

Internal disturbances in the model account for all the potential sources of uncertainty internal to the system and that are translated in deviations in time from planned schedule of flights. Disturbances are related to failures of systems or equipment, human errors, unplanned occurrences, small changes in environmental conditions, etc.

The approach to categorise internal disturbances followed in ATM-NEMMO with the purpose of introducing this “noise” is to cluster them according to flight phases delimited by flight milestones. The milestones used are partially extracted from those defined in A-CDM [5]: milestones selected are related to physical positions of the aircraft throughout the flight taking the airport as a reference. Additionally, two other milestones, not included in A-CDM, are added: Runway Start Time (aircraft at start of runway) and Out of Runway Time (aircraft exits runway). Flight phases considered are: approach, landing, taxi-in, turn-around, taxi-out, take-off, ascent and en-route. Figure 37 depicts the split of a flight into flight phases and the corresponding milestones delimitating each phase.

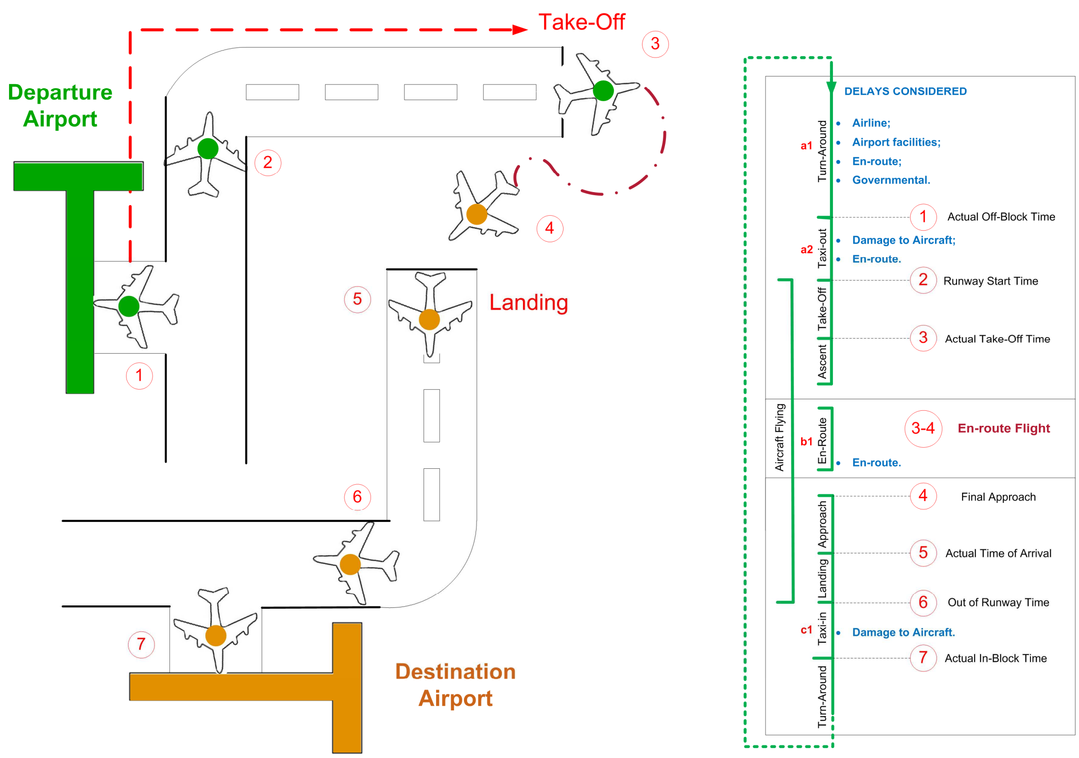

Figure 37 Flight Phases and Internal Disturbances

Within each flight phase, disturbances can come from diverse sources. The classification of sources of disturbances is based on the aggrupation of causes of **primary delay** proposed in CODA [6]:

- Primary delays are, to a great extent, due to internal disturbances of the system, i.e., to the inherent uncertainty of the performance of the system processes and elements.
- In other cases, primary delays can be linked to **external disturbances**, which are produced by an element which is not part of the Air Transport network (e.g. strong weather constraints) and in those cases causes of primary delays are not used as sources of internal disturbances in ATM-NEMMO approach.
- **Reactionary** delay is also excluded from the list, since this issue is modelled explicitly and it is not considered as primary delay cause.
- Other than that, causes related to damage to aircraft and equipment failure during take-off, ascent, en-route, approach and landing (e.g. bird strike, heavy or overweight landing, etc.) are excluded from the analysis since their occurrence can lead to **accidents** and long delays with substitution of aircraft, events that are not modelled in ATM-NEMMO.

Based on the CODA delay causes reproduced in Figure 38, sources of internal disturbances are grouped by flight phase as follows (see also Figure 37):

- Turn-around:

- Airline:
  - Passenger and Baggage;
  - Cargo and Mail;
  - Aircraft and Ramp Handling;
  - Technical and Aircraft Equipment;
  - Damage to Aircraft & EDP/Automated Equipment Failure;
  - Flight Operations and Crewing.
- Airport:
  - Only Airport facilities – parking stands, ramp congestion, lighting, buildings, gate limitations, etc. –.
- En-route:
  - ATFM due to ATC en-route demand/capacity, standard demand/capacity problems;
  - ATFM due to ATC staff/ equipment en-route.
- Governmental:
  - Mandatory security, immigration, customs and health.

- Taxi-out:
  - Airline:
    - Only Damage to Aircraft & EDP/Automated Equipment Failure.
  - En-route:
    - ATFM due to ATC en-route demand/capacity, standard demand/capacity problems;
    - ATFM due to ATC staff/ equipment en-route.
- En-route:
  - En-route:
    - ATFM due to ATC en-route demand/capacity, standard demand/capacity problems;
    - ATFM due to ATC staff/ equipment en-route.
- Taxi-in:
  - Airline:
    - Only Damage to Aircraft & EDP/Automated Equipment Failure.

	CODA CAUSE	Description	IATA Code
Primary Delay Causes	Airline	Passenger and Baggage	11-19
		Cargo and Mail	21-29
		Aircraft and Ramp Handling	31-39
		Technical and Aircraft Equipment	41-49
		Damage to Aircraft & EDP/Automated Equipment Failure	51-58
		Flight Operations and Crewing	61-69
		Other Airline Related Causes	Others
	Airport	ATFM due to Restriction at Departure Airport	83
		Airport Facilities	87
		Restrictions at Airport of Destination	88
		Restrictions at Airport of Departure	89
	En-Route	ATFM due to ATC En-Route Demand / Capacity	81
		ATFM due to ATC Staff / Equipment En-Route	82
	Governmental	Security and Immigration	85-86
	Weather	Weather (other than ATFM)	71-79
		ATFM due to Weather at Destination	84
	Miscellaneous	Miscellaneous	98-99
	Reactionary	Late Arrival of Aircraft, Crew, Passengers or Load	91-96

Figure 38 CODA Delay Causes and IATA Delay Codes [6]

In order to model these sources of internal disturbances in ATM-NEMMO, probabilistic parameters are added to the estimated times used as reference of the flight status. In Figure 37 the parameters identified are a1, a2, b1, c1. These parameters have the form of probabilistic distributions as in the example below:

Impact in terms of length of primary delay (minutes) of causes considered	Probability that a primary delay of this length occurs
On time	62%
5-15 minutes	21%
16-30 minutes	9%
31-60 minutes	5%
>60 minutes	3%

Figure 39 Distribution of Delay Causes [6]

Given that available data in CODA [6] that can be used to characterise the probabilistic distributions are aggregated by CODA cause (see Figure 38), the approach is to aggregate as well parameters a1, a2 and c1 in a single **a1** parameter that is added to DTOT to account for all sources of internal disturbances during flight rotation. Up to date CODA statistics are used to estimate the probabilistic distribution to be input as **a1**.

Further than that, statistics for "En-route" cause are also used for the estimations of the parameter **MaxFD%** (see sections A.2.9 and A.3.4).

Appendix A.3.4 Input Parameters

The customisable parameters included in the model (in green in the diagrams) are summarised below:

- Time Step – indicates, in minutes, the time interval used by the model for executing the algorithms;

Initial Parameters
- Time Step

- Minimum rotation time – minimum time necessary between landing of a flight and take-off of the subsequent flight using the same aircraft. This is the time for taxiing-in, for the passengers to debark, for the aircraft cleaning, technical verifications, etc., for the boarding of passengers for the following flight and for taxiing-out;

Initial Parameters
- Minimum rotation time

- Number of eligible city pairs – Number of busiest city-pairs in Europe;

Initial Parameters
- Nb eligible city pairs

- Grid Size for HDAs – number of equal squares (unitary airspace volumes) of the airspace grid created to detect HDAs. The grid should be defined in a way that for a flight at average cruise speed (800 km/h) takes between 15 to 20 minutes to pass through an unitary airspace volume;

High density areas
- Grid size *(N x N)*
- Density Percentile (*DP%*)

- Density Percentile for HDAs – % of unitary airspace volumes with maximum hourly density below the maximum hourly density used as threshold for retained HDAs. If DP is set to 0, that would mean that all unitary airspace volumes will be set as HDAs; if it is 100, no HDA would be defined. The percentile should be set in a way that number and location of HDAs obtained coincides with the current and expected airspace congestion areas.

- Probability of Flight Cancellation (PFC) – is the % of flights that are cancelled during short-term phase;

Unbalance Traffic Parameters
- Probability of Flight Cancellation (PFC)
- Probability of New Flight (PNF)
- Probability of Change in ETOT (PCE)
- Maximum interval in minutes for change in ETOT (MaxCE)

- Probability of New Flight (PNF) – is the % of flights that are created during short-term phase between most busy city-pairs;

- Probability of Change in ETOT (PCE) – is the % of flights that experiment a change in ETOT during short-term phase due to primary delay causes;

- Maximum interval in minutes for change in ETOT (MaxCE) – indicates, in minutes, the maximum variation in ETOT during short-term phase, of those flights experimenting changes in ETOT allowed in the model;

- Airport and Airspace capacity shortfalls can be defined ad-hoc as part of the scenario parameterisation. The parameters defined are the percentage of shortfall in capacity, the time interval during which it is produced and the anticipation with which it is known to the rest of the network. Additionally, the airspace capacity shortfalls are defined over any airspace area, by introducing lat/lon of three points which will be the limits of the triangular airspace area with capacity restrictions;

SCENARIO Customisation
- Define airport capacity shortfalls
- Define airspace capacity shortfalls

- Capacity Percentage – refers to the % of airport capacity that is reserved for landing of holdings in the TStep of execution;

EXECUTION Parameters
- Capacity Percentage (CP%)

- a1 – is the probabilistic distribution used to introduce uncertainty related to the ability of each flight to fulfil estimated times at the airport. It is based on statistics of primary delays at the airport;

EXECUTION Parameters
- a1

- Maximum variability in flight duration (MaxFD%) – is the % of increase or decrease in flight duration that can be expected for all flights due to en-route variability related to wind, weather conditions, etc.;

EXECUTION Parameters
- Maximum variability in flight duration (MaxFD)

Values for each parameter to populate the model are ideally obtained from ATM statistics.

Appendix A.4 Model Variables (Output Parameters)

There are some process counters that are used as Performance Indicators for the modelling exercises results analysis. There are as follows:

- **HDA flight counter for Tstep of ETO**. For each flight crossing a High Density Area this counter value is increased. It is used at Tj-1 hour and at Tj.
- **Overload counter for the HDA at the Tstep of ETO.** For each flight and each HDA that it crosses the process compares the HDA predicted capacity with the number of simultaneous flights expected at the HDA at the Tstep following the entry of the flight in the HAD. If predicted capacity is expected to be exceeded for Tstep of ETO, an overload occurrence is registered for the HDA at the Tstep of ETO. It is used at Tj-1 hour and at Tj.
- **ADES flight counter for Tstep of ETA** If the flight being checked does not cross any HDA or no overload is expected for crossing it (so no regulation yet), then the process checks capacity at destination airport (ADES). If the capacity at destination airport is not exceeded then the flight is permitted to landing. Thus the ADES flight counter is increased. It is used at Tj-1 hour and at Tj.

- **ADES Overload counter.** If predicted capacity is expected to be exceeded for Tstep of ETA (because of arriving and departing flights to the airport), an overload occurrence is registered for ADES at the Tstep of ETA. It is used at Tj-1 hour and at Tj.
- **Reactionary counter**. Reactionary counter registers all reactionary delays for each airport and Tstep. It is used at Tj.
- **ADES arrivals & departures flight counter for Tj.** Execution of flights at Tj starts processing first arrival flights on hold at ADES. The process lands all flights on hold by order of ETA. Once all flights on hold at Tj have landed or all reserved capacities at ADES have been consumed, the following step processes all the rest of arrivals and departures within Tj. For each flight departure or arrival the counter is increased (Flight execution at Tj).
- **ADEP arrivals & departures flight counter or Tj.** If the flight is a departure and the flight is considered to have a slot time assigned, the counter is increased. It is used at Departures at Tj.
- **Overload counter.** If the flight is a departure and there is not enough capacity at ADEP, the flight is delayed on-ground: a new DTOT (DTOT') is assigned, set at the first minute of T(j+1).The overload counter is increased.

Appendix B ATM-NEMMO User Manual

This User Manual is a technical communication document intended to provide support to people using the ATM-NEMMO model.

The present document is a guide on how to use the main functions of ATM-NEMMO computational model for running diverse simulation exercises. It contains both written guide and associated images and also screenshots of the Human-Machine Interface (HMI). It must be highlighted that the customisable possibilities of the tool exceed the current HMI, and are complemented with software code changes in line with the process diagrams included in Appendix A.

Appendix B.1 Introduction

ATM-NEMMO mathematical model is a simplified representation of the whole ECAC air transport network intended to explore through simulation the network behaviour and performance under different initial and operational conditions.

ATM-NEMMO is a dynamic and stochastic simulation model. The approach is mesoscopic, an intermediate line between microscopic models, which consider the dynamics and detailed routing of every individual vehicle, and macroscopic ones, which focus on system properties as a result of integrating the state of the ATM elements. Mesoscopic models exploit probabilistic methods to account for the microscopic details without losing the macroscopic and strategic view of the system. Results are expressed as probability distributions, linked, for instance, to the probability of having aircraft A at time t in position x.

For the correct understanding of the main functionalities that will be explained in the following subsections it is worthwhile to complement the reading with the 'ATM NEMMO technical specifications' document (attached to this deliverable as Appendix A).

Appendix B.2 Preparing a Simulation Exercise

Appendix B.2.1 Model Initiation Load

The following steps follow the logical flow diagram representing the initiation load of ATM-NEMMO, and which is displayed in Figure 12 in Appendix A.1 and further detailed and explained in Appendix A.2.

Loading Network

The model is loaded with the information in the balanced Network Operation plan (NOP). This 'Balanced NOP' is created using key fields of the Traffic Sample.

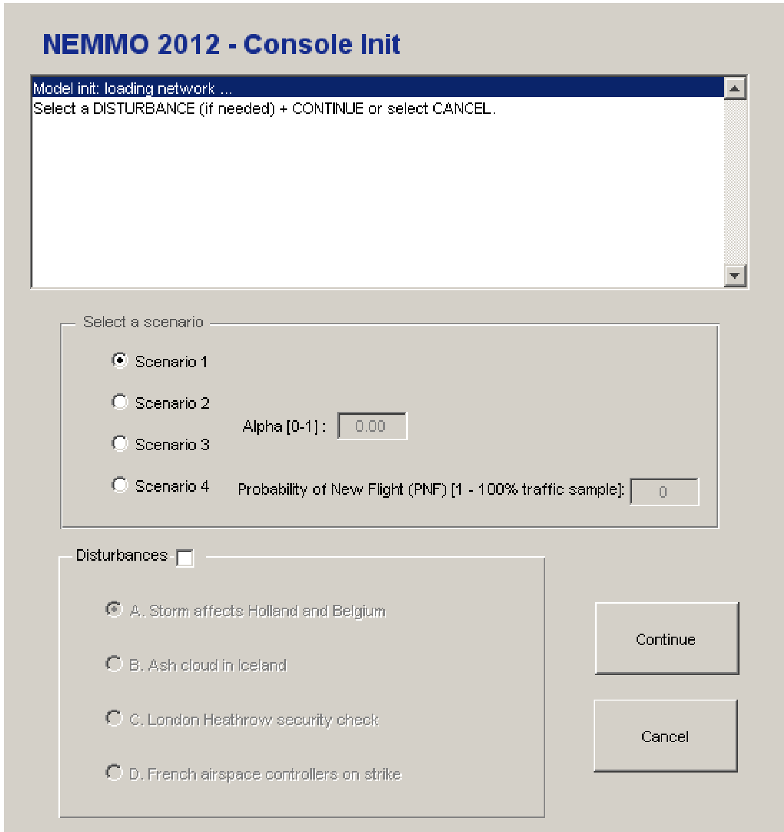

Figure 40 Initial load of ATM-NEMMO

A balanced NOP is the starting point, but for the execution of the simulation runs, this NOP will always have associated certain uncertainty. Initial 'unbalanced NOP' will be obtained from the balanced NOP by processing it according to specific customizable scenarios (i.e.: traffic growth scenarios).

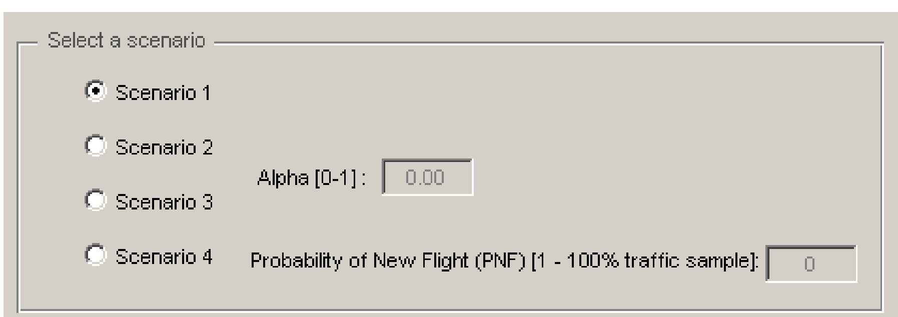

Figure 41 Loading network, selection of a Scenario

It is also possible to introduce specific External Disturbances to the scenario. The set of External Disturbances below are examples representing real past event that caused disruptions at specific airports. In the example below the External Disturbance chosen is the one assigned to 'A'. The characterization of the storm affecting

Holland and Belgium is based on reducing airport capacities (arrivals and departures) at all the affected airports.

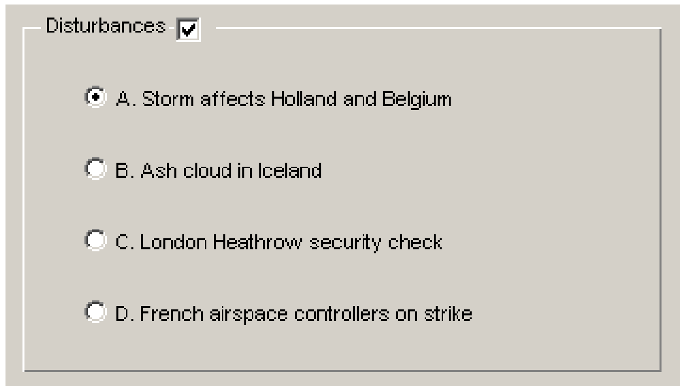

Figure 42 Loading network, selection of External Disturbance

Once Unbalanced NOP and specific scenario and external disturbances are selected and loaded, it is time for the model to load the traffic (*Model init: loading traffic* line in the figure below) and to identify the linked flights in the traffic sample (*Linking*… in the figure below).

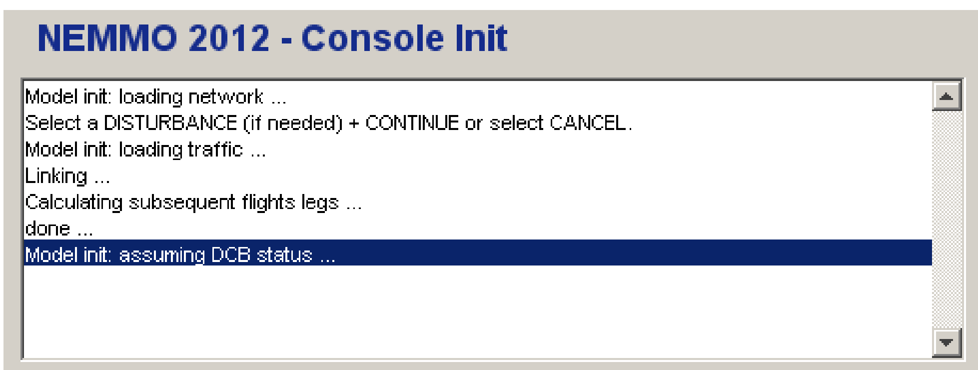

Figure 43 ATM-NEMMO Initiation Console

After flight linking process, the number of subsequent flight legs per flight is calculated in order to store the value internally per flight and use it internally as a support to other flight planning information.

The process called 'assuming DCB status' makes reference to a Demand and Capacity Balance assumed by the tool at this stage of the run.

Airspace and Airport configurations

In addition to the undesirable effects introduced to the system through the selection of external disturbances, it is possible for the user to customize both Airport and Airspace 'capacity shortfalls'. This is done by using the Airport Scenario editor and Airspace Scenario editor functionalities provided by the tool.

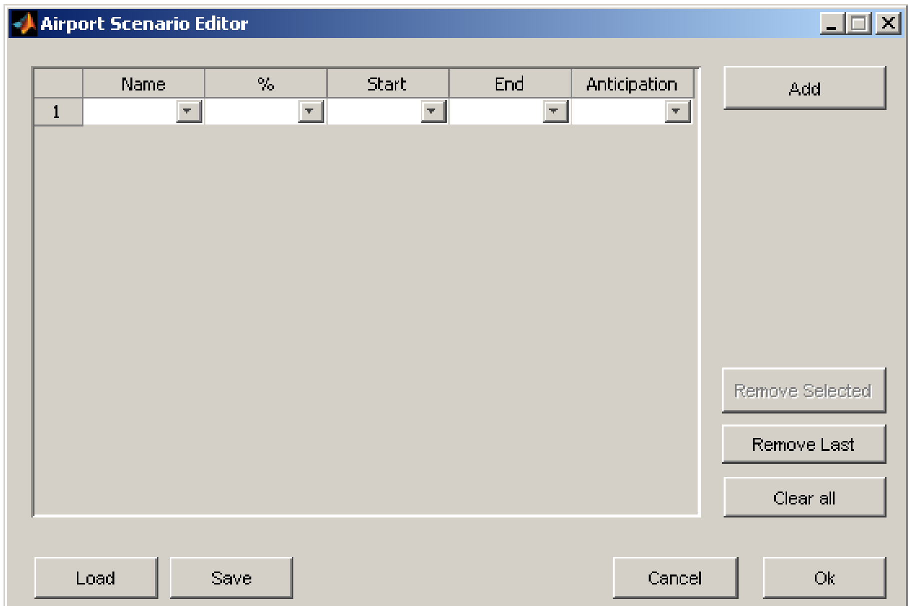

Figure 44 Airport Scenario editor

In the Airport Scenario Editor, the 'impacted airport' is selected in the field 'Name'. After that, the percentage of capacity shortfall is introduced in '% field'. Both, the 'Start' and 'End' times are editable to define the period of time in which the capacity shortfall at the selected airport is active.

Finally, the 'Anticipation' field must be filled in. This refers to the time in advance in which the 'Network' is informed about the capacity shortfall at the selected airport (see section 2.3.2). The more time in advance the network is informed the better traffic flow adaptation will be performed. If for example, the anticipation is set in 5 minutes, it is more than quite probable that the system will not be able to readapt the traffic flows in advance and the capacity shortfalls defined for this specific airport will impact to the rest of the flights linking many other airports, producing high disruptions in overall network.

This could be done for as many airports as desired.

As for the Airspace configuration the tool permits defining High Density Areas. This means that each flight crossing this Area will be impacted and affected by the capacity constraints.

The Longitude and Latitude fields should be filled in to define the airspace square constituting a High Density Area. The capacity limitation is indicated in 'Capacity' and 'Start' and 'End' times are set as in the example above. The Anticipation is also editable.

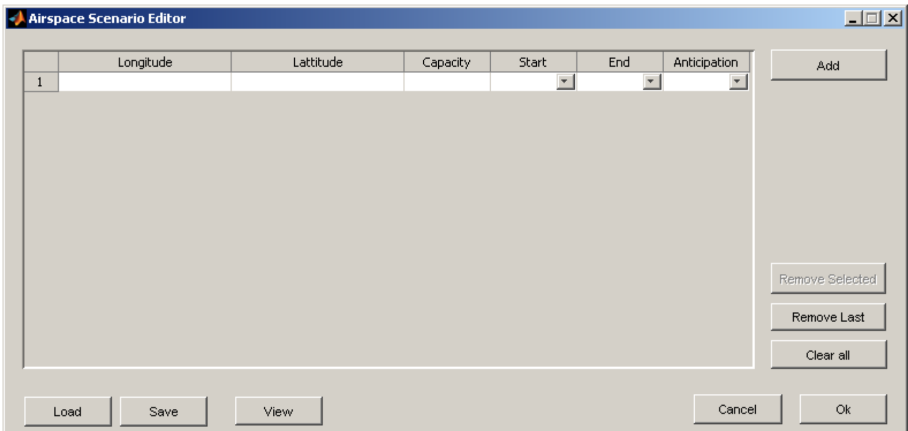

Figure 45 Airspace Scenario editor

At this stage Airports and Airspace configurations are set and now it is time to introduce variability in Traffic and Airport processes.

Appendix B.2.2 ATM NEMMO Input Parameters

The customisable parameters included in the model are described in Appendix A.3.4.

Except the parameter 'a1', which is an internal parameter, the rest of the Input Parameters are editable in the tool.

The values assigned to the Input Parameters in the example below are based on statistical analysis of real sources of data. However, for the set of the Safety Enhancement Systems under study in WP3.4 the values of the Initial Parameters will be defined in terms of the expected impact.

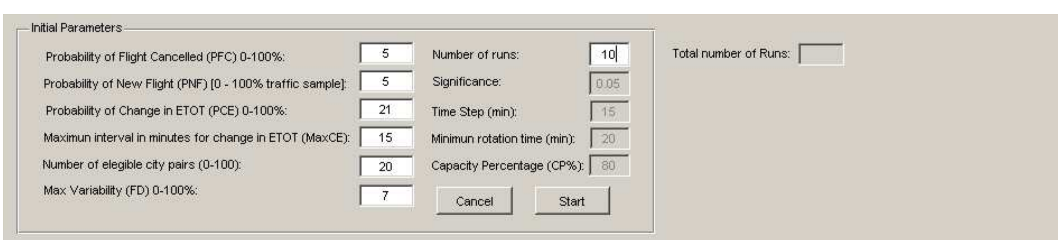

Figure 46 ATM NEMMO Input Parameters

At this stage, the airspace, airports and traffic characteristics are edited and introduced in the tool. The execution starts and the model pass through different intermediate steps where different types of results are provided.

Appendix B.2.3 Complete Model Load

After the customisable Input Parameters are set, the last steps of the logical flow diagram representing the initiation load of ATM-NEMMO (see Figure 12 in Appendix A.1) are completed:

- City-pairs are identified (see Appendix A.2.4);
- Airspace High Density Areas are established (see Appendix A.2.5);
- and traffic is unbalanced (see Appendix A.2.6).

These are internal processed performed by the model that require no human interaction. However, they are listed here to provide a complete view of the model performance.

Appendix B.3 Execution Run

The simulations are based typically on one day traffic operations and Montecarlo [2]technique.

For each simulation run, the tool is prepared to calculate values for the Local and Global Performance Indicators defined in Appendix A.4 and further detailed in section 2.3.3. Since Montecarlo simulations are performed, the way in which the results are shown is based on Histograms where average values of Indicators are depicted per one hour time intervals.

At the end of simulation runs the tool is prepared to represent, in addition to the average values of Performance Indicators, the traffic density at overall network level, which is a static picture where the overall daily performance is represented.

2 Monte Carlo methods are a broad class of computational algorithms that rely on repeated random sampling to obtain numerical results; i.e., by running simulations many times over in order to calculate those same probabilities heuristically just like actually playing and recording your results in a real casino situation: hence the name. They are often used in physical and mathematical problems, mainly in optimization, numerical integration and generation of samples from a probability distribution.

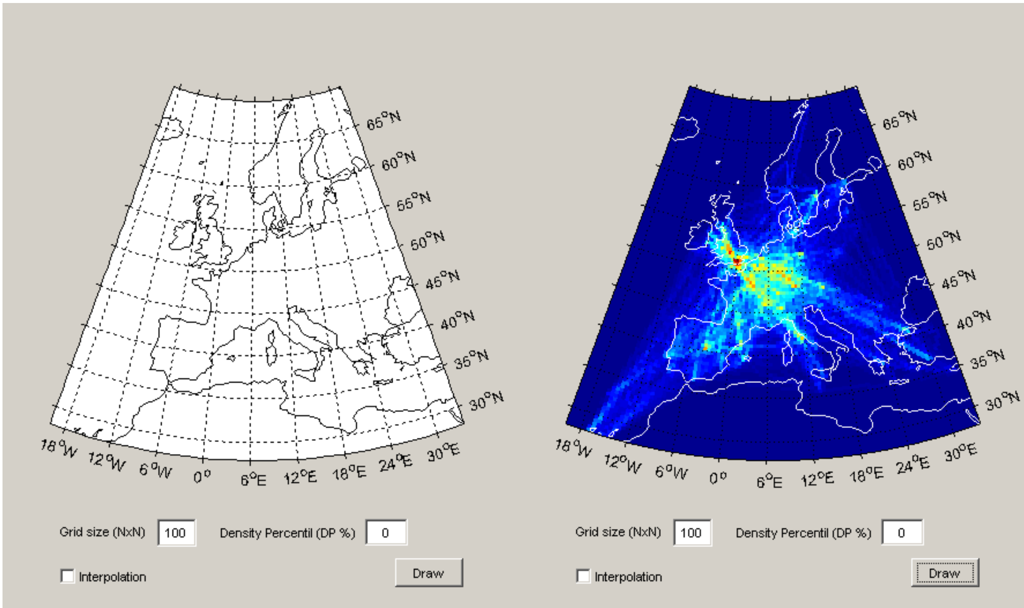

Figure 47 ATM NEMMO Traffic Density (before and after runs)

In the figure below, the Histograms on top show the values of Global Indicators (values for overall network, at European Level) and the ones on the bottom represent the average values at specific airports (it is possible for the user to select each airport, one by one).

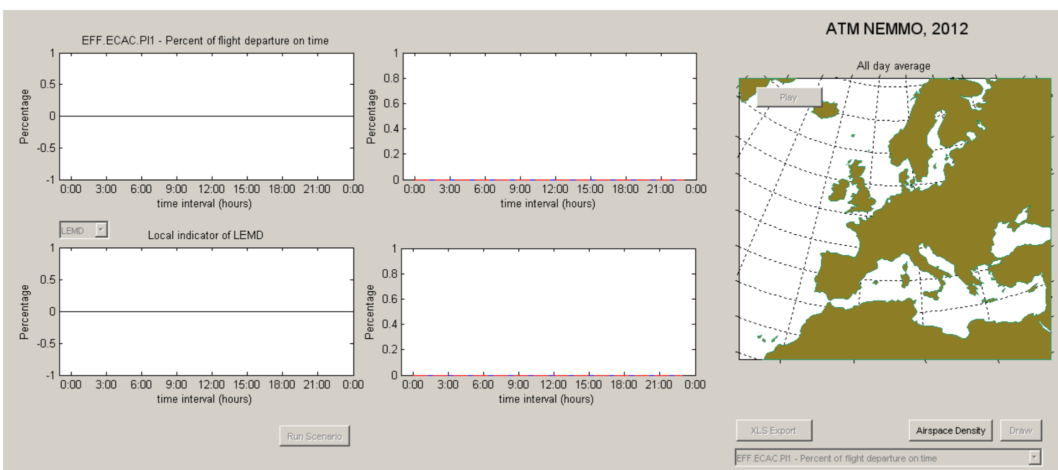

Figure 48 ATM NEMMO Performance Indicators Screen

On the right side, the ECAC (European Civil Aviation Conference) area is represented. During the executions, all the airports in the network are depicted by a circle and the congestion level or evolution is represented based on a colour code. An example including the values after simulations is shown in the next section.

Appendix B.4 Simulation Results

The diagram below shows an example with the values for the 'Number of Overload' metric calculated by the tool at Global (Overall Network on top) and Local level (per each Airport inside the Network, at the bottom).

According to the results shown, for the overall network, the number of overloads arrives at around 700 in specific time periods of the day while at LFSB airport (Basel-Mulhouse airport, ICAO code) just few overloads appear at 6.00-9.00 and 15.00-21.00 periods of the day. The diagrams in the right side represent the average and standard deviation of the Indicator.

The diagram representing the ECAC area on the right side shows the evolution of the congestion level at each airport. This is in principle a dynamic graph where the congestion level is represented at hourly basis.

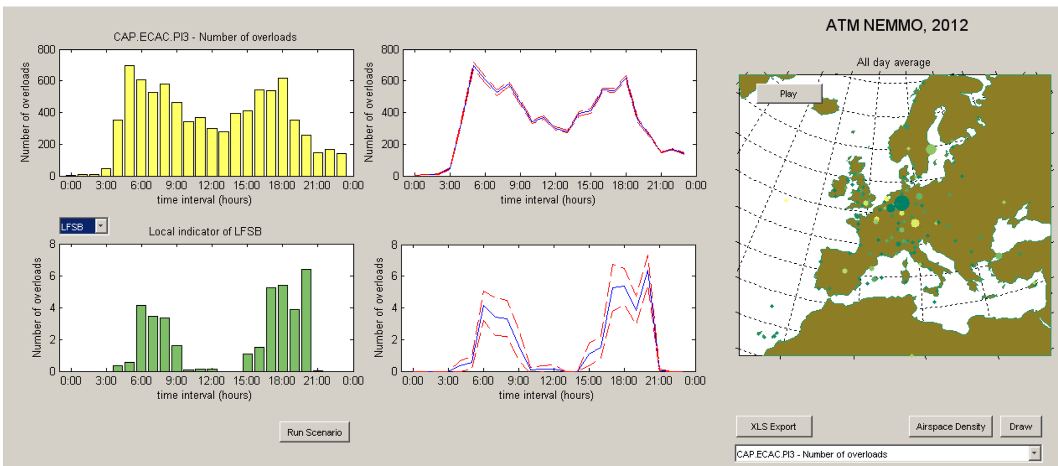

Figure 49 ATM NEMMO Performance Indicators

The results for all the Indicators (global and local) (see Appendix A.4 and section 2.3.3) and airports (133 airports) are also exported to an excel sheet. This makes possible to perform the statistical analysis of the simulation results.

Appendix B.5 Statistical Significance of the Results

In a research context, statistical significance simply conveys that the 'probability of the observed difference arising by chance was sufficiently small' (Norman & Streiner, 2003, p.32). This does not refer to the size of the difference or whether the difference is meaningful. To address meaningfulness, researchers can report and interpret an effect size estimate. Before discussing effect size, it is important to recall a point about statistical significance.

Statistical analysis indicates whether a non-zero difference between groups is likely to be a random occurrence or if it is likely to be found again and again if the study is repeated; thus, statistical significance is based on estimates of probabilities. The first point concerns interpretation of ρ values, the most common metric by which statistical significance is determined. Most often, a finding of statistical significance is one in which a particular test value corresponds to a probability estimate of less than 0.05; the chance that this finding is spurious is less than 5%. The ρ value concerns only probability, not important findings.

For the simulation results' statistical analysis, the following tests are performed:

- Test for Normal Distribution: Kolmogorov-Smirnov with Lilliefors correction and Saphiro-Wilk;
- Significance level, and;
- Effect size.

Appendix C Connection ATM-NEMMO – CATS

The table below specifies the type of links between ATM-NEMMO Performance Indicators (introduced in section 2.3.3) and CATS base events [12]. The list of base events is restricted to those considered to being impacted by changes in values of PIs with regards to the baseline scenario (see sections 2.3.4 and 5). The impact is always in terms of variation of the probability of occurrence of the base event. In the intersection between each base event and each PI, the following information is displayed:

- ⊕: meaning that an increase in the PI with regards to the baseline scenario is linked to a potential increase in the probability of occurrence of the base event;
- Θ: meaning that an increase in the PI with regards to the baseline scenario is linked to a potential decrease in the probability of occurrence of the base event;
- Rationale for the potential impact on the base event.

The reference code of the base events is taken preferably from Appendix D of ASCOS D3.2 [12]. For those base events used in several ESDs, the reference to the first ESD in which they appear is used. Finally, for the base events related to ESDs not included in Appendix D of ASCOS D3.2, the reference in D3.2 FT diagrams in Appendix B of the same document are used.

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
Pilot misdiagnosis – TO01B211		ϴ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Pilot misjudgement – TO01B212		ϴ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Take-off instruction error by ATCO – TO02B11111	⊕ High workload generating distress, fatigue and time pressure	ϴ Smooth traffic situation inducing less fatigue and time pressure	⊕ High workload generating distress, fatigue and time pressure			
Inadequate communication with	⊕ High workload generating distress,	ϴ Smooth traffic situation inducing	⊕ High workload generating distress,			⊕ Increase in flight crew distress and

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
pilot – TO02B11112	fatigue and time pressure	less fatigue and time pressure	fatigue and time pressure/ Increase in flight crew distress and probability of human errors			probability of human errors
Pilot failure to follow take-off instructions – TO02B1112		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Separation Infringement with Departing Aircraft caused by other a/c - TO02B11211	⊕ High traffic density, potentially complex, reducing margin for trajectory deviations	Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors	⊕ Increase in flight crew distress and probability of human errors	⊕ Increase in flight crew distress and probability of human errors	⊕ Increase in flight crew distress and probability of human errors

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
Separation Infringement with Landing Aircraft caused by other a/c - TO02B11212	⊕ High traffic density, potentially complex, reducing margin for trajectory deviations	Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors	⊕ Increase in flight crew distress and probability of human errors	⊕ Increase in flight crew distress and probability of human errors	⊕ Increase in flight crew distress and probability of human errors
Separation Infringement with a/c on missed approach - TO02B11213	⊕ High traffic density, potentially complex, reducing margin for trajectory deviations	Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors	⊕ Increase in flight crew distress and probability of human errors	⊕ Increase in flight crew distress and probability of human errors	⊕ Increase in flight crew distress and probability of human errors
Separation Infringement with departing a/c caused by aircraft taking off - TO02B11214	⊕ High traffic density, potentially complex, reducing margin for trajectory deviations	Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
Separation Infringement with landing a/c caused by aircraft taking off - TO02B11215	⊕ High traffic density, potentially complex, reducing margin for trajectory deviations	ϴ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors	⊕ Increase in flight crew distress and probability of human errors	⊕ Increase in flight crew distress and probability of human errors	⊕ Increase in flight crew distress and probability of human errors
Illegal A/C infringement - TO02B11216	⊕ High traffic density, potentially complex, reducing margin for trajectory deviations	ϴ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors	⊕ Increase in flight crew distress and probability of human errors	⊕ Increase in flight crew distress and probability of human errors	⊕ Increase in flight crew distress and probability of human errors
Traffic density too high - TO02B1122	⊕ High traffic density, potentially complex, reducing margin for trajectory deviations and					

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
	increasing ATC workload (distress, more fatigue and time pressure)					
Aircraft not ready to take-off – TO02B1123		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Unsuccessful handling due to lack of training - TO03B111		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Unsuccessful Handling - TO03B112		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Lack of control - TO03B32		Θ Smooth traffic situation inducing	⊕ Increase in flight crew distress and			⊕ Increase in flight crew distress and

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
		less fatigue and time pressure	probability of human errors			probability of human errors
Incorrect Control - TO03B33		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Unsuccessful TO configuration checklist - TO05B111		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Unsuccessful Checklist Verification - TO05B112		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Flap & slat positions entered into FMC incorrectly - TO05B12		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
Verification not conducted - TO05B21		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Verification unsuccessful - TO05B22		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Unsuccessful Operation - TO05B313		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Aircraft takes-off with incorrect configuration - TO05B33		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Pilot ignores stick shaker - TO05B622		Θ Smooth traffic situation inducing	⊕ Increase in flight crew distress and			⊕ Increase in flight crew distress and

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
		less fatigue and time pressure	probability of human errors			probability of human errors
Flight crew does not regain control – ASC06b12		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Crew fail to recognise windshear – ASC08b112		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Failure of ATC to advise pilot – ASC08b1113	⊕ High workload generating distress, fatigue and time pressure	Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ High workload generating distress, fatigue and time pressure			
Trim settings incorrectly determined - TO10B1111		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
Speed settings incorrectly determined - TO10B1112		ϴ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Trim settings incorrectly entered into FMC - TO10B112		ϴ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Speed settings incorrectly entered into FMC - TO10B113		ϴ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Unsuccessful Pitch Control Inputs - TO10B12		ϴ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Crew Misdiagnose Situation - TO10B211		ϴ Smooth traffic situation inducing	⊕ Increase in flight crew distress and			⊕ Increase in flight crew distress and

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
		less fatigue and time pressure	probability of human errors			probability of human errors
Crew Misjudge Situation - TO10B212		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Pitch Control Misdiagnosed - TO10B41		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Unsuccessful Pitch Control Rectification - TO10B42		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress and probability of human errors			⊕ Increase in flight crew distress and probability of human errors
Incorrect recovery action – ASC12b123	⊕ High traffic density, potentially complex, reducing margin for			⊕ Increase in flight crew distress, fatigue and probability of	⊕ Increase in flight crew distress, fatigue and probability of	⊕ Increase in flight crew distress, fatigue and probability of

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
	trajectory deviations			human errors	human errors	human errors
Insufficient recovery action - ASC12b124	⊕ High traffic density, potentially complex, reducing margin for trajectory deviations			⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors
Unsuccessful flight crew depressurization response – ASC14a112	⊕ High traffic density, potentially complex, inducing distress and fatigue			⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors
Unsuccessful flight deck procedures – ASC14a122	⊕ High traffic density, potentially complex, inducing distress and fatigue			⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
Medical incapacitation of the pilot – ASC14a122	⊕ High traffic density, potentially complex, inducing distress and fatigue			⊕ Increase in flight crew distress and fatigue	⊕ Increase in flight crew distress and fatigue	⊕ Increase in flight crew distress and fatigue
Lack of response to pilot incapacitation – ASC14b12	⊕ High traffic density, potentially complex, inducing distress and fatigue			⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors
Incorrect response to pilot incapacitation – ASC14b13	⊕ High traffic density, potentially complex, inducing distress and fatigue			⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors
Flight crew does not avoid unfavourable weather conditions – ASC17a112	⊕ High traffic density, potentially complex, inducing distress and fatigue			⊕ Increase in flight crew distress, fatigue and probability of	⊕ Increase in flight crew distress, fatigue and probability of	⊕ Increase in flight crew distress, fatigue and probability of

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
				human errors	human errors	human errors
Flight crew shuts down wrong engine – ASC18b13	⊕ High traffic density, potentially complex, inducing distress and fatigue			⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors
Poor manual flight control causes unstable approach – ASC19a111				⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors
ATCO trajectory instructions lead to conflicting course – ASC31a14	⊕ High workload generating distress, fatigue and time pressure					
Other ATCO does not detect conflict – ASC31b122	⊕ High workload generating distress, fatigue and time					

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
	pressure					
ATCOs do not communicate – ASC31b123	⊕ High workload generating distress, fatigue and time pressure					
ATCO does not recover separation – ASC31b124	⊕ High workload generating distress, fatigue and time pressure					
Pilot does not respond to RA in time – ASC31c1212	⊕ High traffic density, potentially complex, inducing distress and fatigue			⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors
Flight crew does not detect other visual aircraft – ASC31c1212	⊕ High traffic density, potentially complex, inducing distress and fatigue			⊕ Increase in flight crew distress, fatigue and probability of	⊕ Increase in flight crew distress, fatigue and probability of	⊕ Increase in flight crew distress, fatigue and probability of

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
				human errors	human errors	human errors
Pilot does not take effective avoidance action in time - ASC31c1213	⊕ High traffic density, potentially complex, inducing distress and fatigue			⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors
Pilot receives inadequate runway entry instructions, resulting in a runway incursion – ASC32a111		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors
Pilot does not follow the runway entry procedures and causes a runway incursion – ASC32a112		Θ Smooth traffic situation inducing less fatigue and time pressure	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors
ATCO does not respond to RIMCAS	⊕ High workload generating distress,					

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
warning in time – ASC32b113	fatigue and time pressure					
ATCO does not resolve conflict in time after RIMCAS warning – ASC32b114	⊕ High workload generating distress, fatigue and time pressure					
ATCO does not see visible conflict in time – ASC32b123	⊕ High workload generating distress, fatigue and time pressure					
Improper CRM due to fatigue, resulting in poor airmanship – ASC38a112	⊕ High traffic density, potentially complex, with less margin for trajectory deviations, inducing distress and fatigue			⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
Improper CRM due to undesirable pilot behaviour, resulting in poor airmanship – ASC38a113	⊕ High traffic density, potentially complex, with less margin for trajectory deviations, inducing distress and fatigue			⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors
Poor airmanship displayed by individual pilot caused by fatigue – ASC38a123	⊕ High traffic density, potentially complex, with less margin for trajectory deviations, inducing distress and fatigue			⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors	⊕ Increase in flight crew distress, fatigue and probability of human errors
Pilot's behaviour is undesirable, resulting	⊕ High traffic density, potentially			⊕ Increase in flight crew distress,	⊕ Increase in flight crew distress,	⊕ Increase in flight crew distress,

	Performance Indicator (PI)					
	CAP.PI 2	EFF.PI 1	EFF.PI 2	PRED.PI 1	PRED.PI 2	PRED.PI 3
	Unit					
CATS Base Event	Hourly throughput overloads	Percentage of flight departing on time	Average departure delay per flight (min)	Percentage of delayed flights	Average delay of delayed flights	Reactionary delay (min)
in poor airmanship – ASC38a124	complex, with less margin for trajectory deviations, inducing distress and fatigue			fatigue and probability of human errors	fatigue and probability of human errors	fatigue and probability of human errors