Delft University of Technology
Faculty of Electrical Engineering, Mathematics and Computer Science
Delft Institute of Applied Mathematics

Master of Science Thesis

System Level Risk Analysis of New Merging and Spacing Protocols

by

Gabriela Florentina Singuran

Delft, The Netherlands
July 2008

Members of the committee

Chairperson of Graduate Committee: Prof. Dr. R.M. Cooke
(Supervisor)

Graduate committee:

Prof. Dr. R.M. Cooke	Faculty of Electrical Engineering, Mathematics and Compute Science, Department of Applied Mathematics, Delft University of Technology and Resources for Future
Dr. D. Kurowicka	Faculty of Electrical Engineering, Mathematics and Compute Science, Department of Applied Mathematics, Delft University of Technology
Prof. Dr. B.J.M. Ale	Faculty of Technology, Policy and Management, Delft University of Technology
A.L.C. Roelen	National Aerospace Laboratory (NLR)

Abstract

Title: System level Risk Analysis of New Merging and Spacing Protocols

by

Gabriela Florentina Singuran

The purpose of this project is to apply the Causal Model of Air Transport Safety (CATS) to assess the risk benefits and risk penalties implied by NASA's new Merging and Spacing concept. The goal of the new concept is to increase runway throughput. Increasing throughput without a corresponding reduction in the accident probability per flight would result in a higher accident incidence, and higher perceptions of air transport risk. A system wide risk model, like the CATS model, can be employed to quantify the risk consequences of the new merging and spacing concept.

CATS was commissioned by the Dutch Ministry of Transport and is being developed by a consortium including Delft University of Technology, National Aerospace Laboratory (NLR), Det Norske Veritas (DNV) and White Queen. The project arose from a need for a thorough understanding of the causal factors underlying the risks of air transport, so that efforts to improve safety can be made as effective as possible. This can be achieved by developing a fully operational causal model that represents the causes of commercial air transport accidents and the safeguards that are in place to prevent them. The underlying software tool, UNINET, was developed at the Delft Institute of Applied Mathematics of the Delft University of Technology to enable the mathematical representation of the model through a powerful mathematical tool, the Bayesian Belief Nets (BBNs).

The CATS model can be used to identify areas for improvement to the technical and managerial safeguards against accidents and to quantify the risk implications of alternative technical and management changes. The model is therefore an appropriate tool to explore the risks implied by NASA's Merging and Spacing concept. This concept aims to safely increase the traffic capacity via precise spacing at the runway threshold. In order to meet the forecasted growth, advanced airborne decision support tools are being developed to assist the flight crew in achieving precise spacing behind another aircraft. By considering all possible influences on and of the merging and spacing and by quantifying the risk benefits as well as the risk penalties implied by the concept, subsequent risks assessments can be translated, using the CATS model structure, into risk implications of the Merging and Spacing concept.

To my family

Table of contents

Acknowledgements iii
List of figures v
List of Tables vii
1. Introduction 1
  1.1. The risk perspective 1
  1.2. Thesis outline 5
2. Airborne Precision Spacing in Merging Arrival Streams (M&S) 7
  2.1. Introduction 7
  2.2. The Development of Airborne Precision Spacing Concept 7
  2.3. Concept of Operations and Flight Crew Procedures 11
  2.4. Fast – Time Study Experiments 14
  2.5. Evaluation of the Concept in a Human-in-the-Loop Simulation 18
3. The Causal Model for Air Transport Safety (CATS) 25
  3.1. Introduction 25
  3.2. Event Sequence Diagrams (ESDs) 25
  3.3. Fault-Trees (FTs) 28
  3.4. Bayesian Belief Nets (BBNs) 29
    3.4.1. Discrete BBNs 30
    3.4.2. Normal BBNs 30
    3.4.3. Non-parametric BBNs 31
  3.5. The Overall Network Model 35
4. A Merging and Spacing (M&S) Approach to the CATS model 39
  4.1. Assumptions 39
  4.2. Changes in ESDs and FTs 40
  4.3. Changes in BBNs 44
  4.4. Communication 45
5. Numerical Results 51
  5.1. Quantification of the assumptions 51
  5.2 Three approaches to quantification 52
6. Future extensions 57
7. Conclusions 59
Bibliography 61
Appendix A 63
Appendix B 65
Appendix C 67
Appendix D 69
Appendix E 73
Appendix F 75
Appendix G 77
Appendix H 87

Appendix I 89
Appendix J 91
Appendix K.. 93
Appendix L 97

Acknowledgements

Firstly, I would like to thank Prof. Roger Cooke and Prof. Dorota Kurowicka for giving me the opportunity to participate in this Master program. I remember Prof. Roger Cooke telling us in September 2006 that these two years will be our most beautiful years. I can honestly say now that I totally agree with him. For me, this period did not only imply vast academic achievements, but also an occasion to meet great people.

Once again, I would like to express my indebted gratitude to Prof. Roger Cooke for giving me the enormous opportunity to work for this project. The time spent together and the constant support accounted for more than enough motivation to exceed my limits and to wish for more. I also want to thank him for the chance to develop my non-mathematical skills.

I would like to thank Oswaldo Morales Napoles for his great help throughout the whole project, especially under the given time pressure. Also, I would like to thank Kasia ("my Kasia") for her help with the model and for being the best officemate, but more important a great friend in these two years.

I would like to thank Dan for his help with the short-notice changes that I needed for Uninet. Moreover, I would like to thank to all my friends that had to bear my continuous (or hopefully not) stress and complaints. As promised, I will provide a list with all the books I will read during holidays and additionally I will also provide pictures with the "non-stressed" Tina.

I would like to thank my family for their unconditional love and constant support. I am grateful my father for the strong encouragement to pursue this path and for the technical feedback during this project. I would like to thank my mother for her hard-times advice and support. Nevertheless, I just want to thank my brother for being the best brother in the world. I miss you everyday!

Finally, I would like to thank my love, Răzvan for his unlimited help and support and for constantly having more faith in me than myself. I also thank him for his understanding and support in my decisions and for bearing the three endless months that we were apart. I dedicate this work to him with all my love.

List of figures

Figure 1.1 Number of accidents involving at least one fatality within 30 days (red bars) and number of flights (x million) (blue line) from 1980 to 2003, for world wide commercial aircraft with take-off weight of 5700 kg or heavier. 1
Figure 1.2 Fatal accidents (at least one fatality within 30 days) with commercial aviation (take off weight 5700 kg or heavier), per million flights, world wide (red) and for EASA (blue). 2
Figure 1.3 Principal causes of fatal accidents for commercial aviation (take off weight > 5700kg), categorized according to the International Civil Aviation Organization, 1989-2003... 2
Figure 1.4 Relative importance of contributing factors to fatal accidents with commercial aviation (take off weight > 5700 kg) where a contributing factor is "a decisive factor in the causal chain of events leading to a fatal accident", 1980-2003. 3
Figure 1.5 U.S. commercial airport operations (x million), forecasts and realizations, according to FAA terminal area forecast reports, between 1997 and 2006....................... 4
Figure 1.6 U.S. enplanement forecasts and realizations (x million), according to FAA terminal area forecast reports, between 1997 and 2006... 4
Figure 3.7 ESD31 – Aircraft are positioned on collision course. 26
Figure 3.8 Part of the FT associated with ESD31 29
Figure 3.9: Example of a simple BBN, where a child node has two parent nodes........... 30
Figure 3.10: BBN representing the Flight Crew Performance model in the CATS model 32
Figure 3.11: Example of BBN with 5 nodes. The dependence relationships are specified using (conditional) rank correlations. 34
Figure 3.12: CATS overall network model... 36
Figure 4.13: Flight Crew performance model and ATCo performance model connected with the new added variable, Total Transmission Time. 47

List of Tables

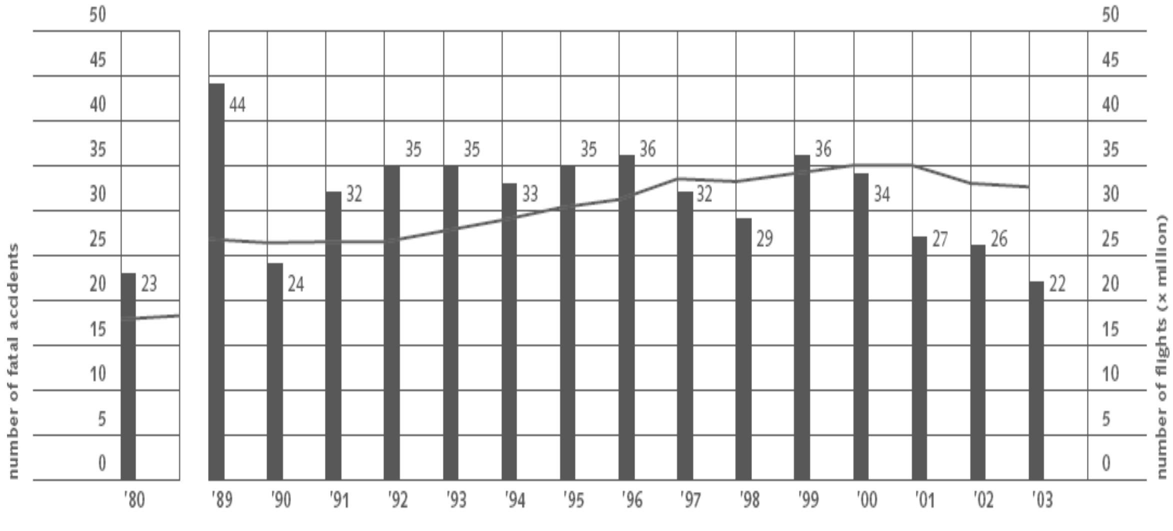
Table 4.1: End events of the affected ESDs, which might result in an accident. 41
Table 4.2: Probabilistic sensitivity methods for the end events in the influenced ESDs.. 42
Table 4.3: Probabilistic sensitivity methods for the first 30 most important end events.. 43
Table 4.4: Probabilistic sensitivity methods for the contributing factors in the human performance models 48
Table 6.5 Percent reduction in accident rate due to assumptions (aircraft generation and surveillance technology), in CATS model, relative to CATS baseline. 51
Table 6.6 Percent reduction in accident rate due to M&S induced reduction in total transmission time, in CATS model, relative to CATS baseline (with assumptions)......... 52
Table 6.7 Percent reduction in accident rate as consequence of M&S protocols, in CATS, relative to CATS baseline (with assumptions)... 54
Table 6.8 Percent reduction in accident rate as consequence of M&S protocols with doubling of traffic volume, in CATS, relative to CATS baseline (with assumptions)..... 55
Table 6.9 Percent reduction in accident rate as consequence of M&S protocols with doubling of traffic volume, in CATS, relative to CATS with doubling the volume (and assumptions). 56

1. Introduction

1.1. The risk perspective

World wide aviation data shows an increase in volume in all types of air transportation. A representative graph from the Dutch Civil Aviation Safety Data 1989-2003 [20] shows the number of flights doubling between 1980 and 2001.

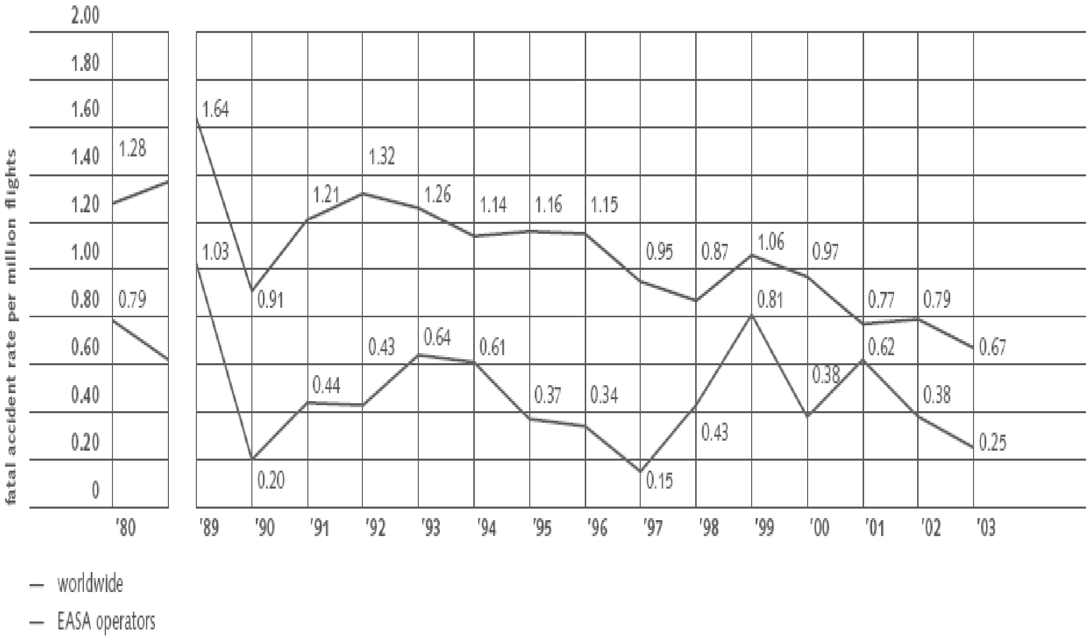
Figure 1.1 Number of accidents involving at least one fatality within 30 days (bars) and number of flights (x million) (line) from 1980 to 2003, for world wide commercial aircraft with take-off weight of 5700 kg or heavier.



The world wide frequency of accidents (number per year) shows no marked trend. However, as pointed out in [20], although the number of accidents has doubled since 1980, the number of fatal accidents has not doubled within this period.

Nonetheless, the number of accidents per flight is decreasing, both world wide and for European Air Safety Agency countries (see Figure 2). A list with all EASA countries can be found in Appendix K. Whereas world wide, the accident rate has been deceasing by 2.8% per year, for EASA countries, the fatal accident rate is deceasing by 4.9% per year.

Figure 1.2 Fatal accidents (at least one fatality within 30 days) with commercial aviation (take off weight 5700 kg or heavier), per million flights, world wide (above) and for EASA (below).



The breakdown in types of accidents shows that collision with ground, which also includes controlled flight into terrain (CFIT) and loss of control in flight are the dominant accident types. They also involve the most fatalities.

Figure 1.3 Principal causes of fatal accidents for commercial aviation (take off weight > 5700kg), categorized according to the International Civil Aviation Organization, 1989-2003. The number of fatalities corresponding to principal causes of fatal accidents is also shown.

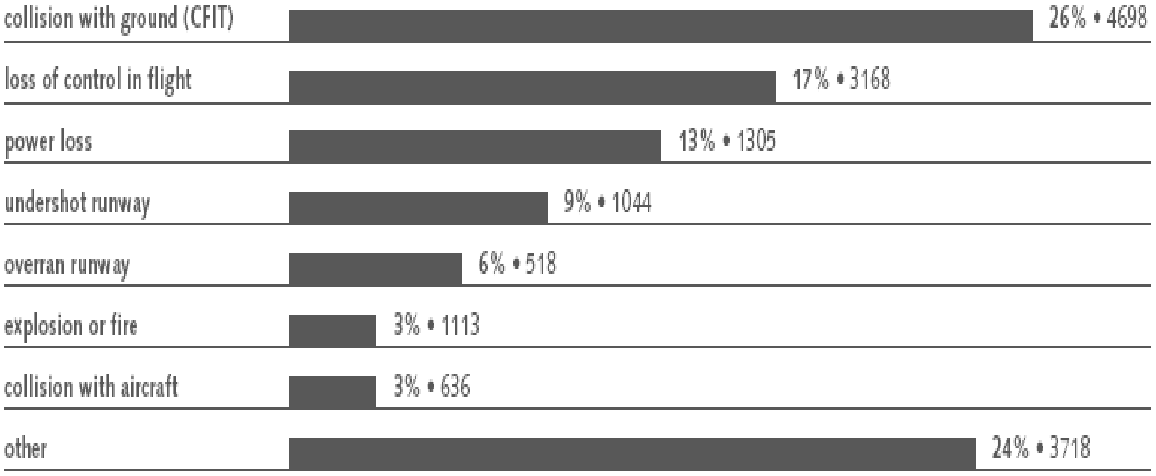
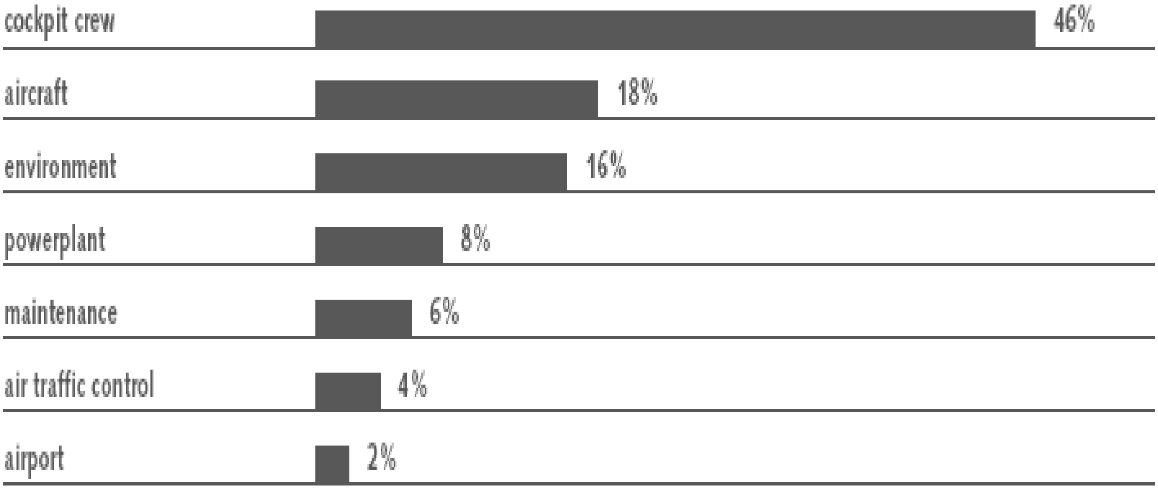


Figure 1.4 Relative importance of contributing factors to fatal accidents with commercial aviation (take off weight > 5700 kg) where a contributing factor is "a decisive factor in the causal chain of events leading to a fatal accident", 1980-2003.

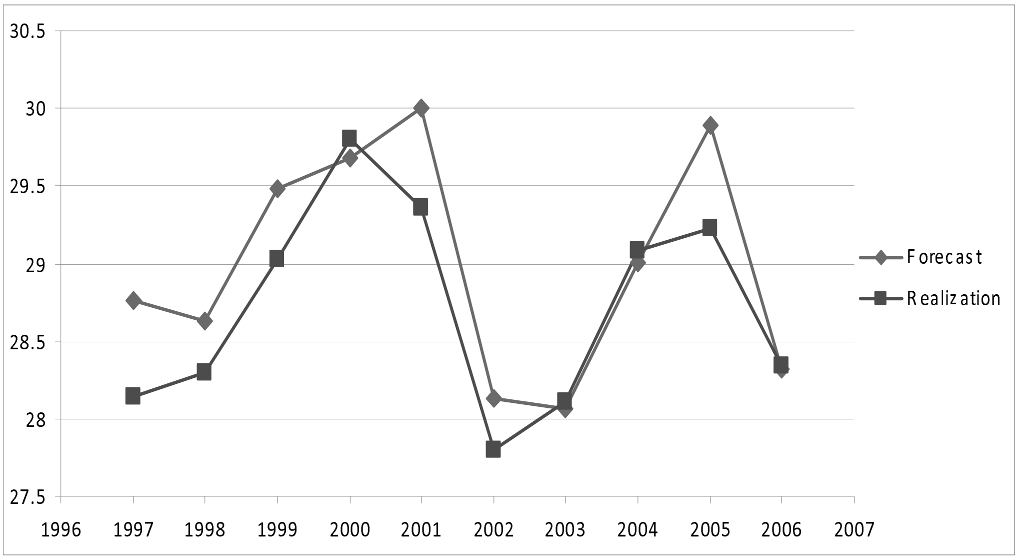


The main causal contributor is represented by the "cockpit crew" (46%). According to this distribution, the human factor is a contributing factor for 56% of the fatal accidents in commercial aviation. Hence, the striking need for a risk model which appropriately describes the human factor and its significance in the causal chain of events leading to a fatal accident.

According to Federal Aviation Administration [16], the aviation system capacity is forecast to grow by 4.4 percent per year up to 2020, which will nearly double the 2006 levels. Significant traffic jams at the runway threshold and consequent aircraft delays are therefore anticipated. Even a small increase in the arrival rate or the runway throughput could lead to a significant reduction in delay for aircraft in the arrival streams. Throughput can be increased by building new runways; however this poses significant economic and environmental challenges. Another approach might involve reducing the separation buffer added to the minimum separation criteria between aircraft, by increasing the precision delivery of aircraft at the runway threshold. This motivated the Merging and Spacing (M&S) approach.

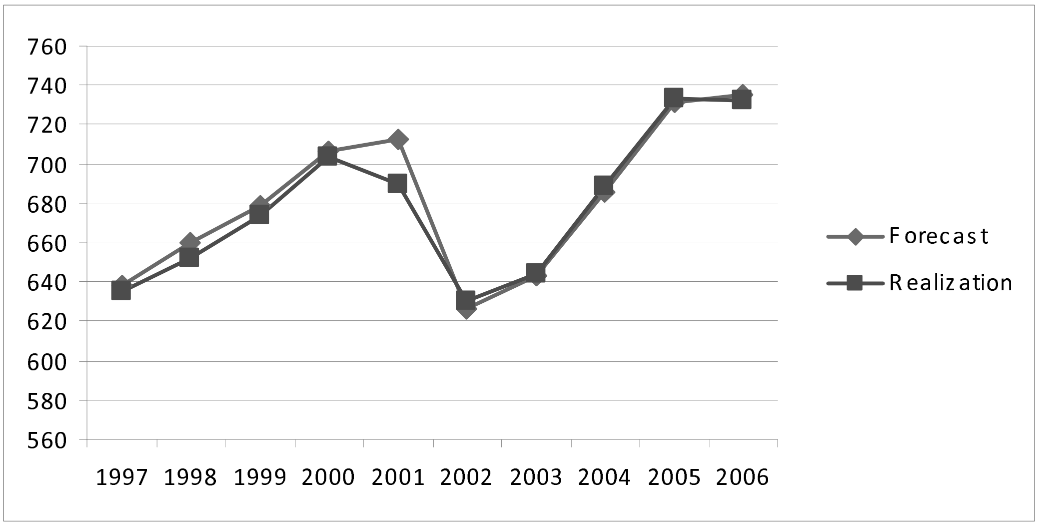
To gain same insight about the forecasted traffic growth, the short-term FAA forecasts have been compared with their corresponding realizations. The two pictures below present the comparison for the U.S. commercial airport operations and U.S. enplanements, between 1997 and 2006. In figure 1.5, the highest differences can be observed for the years 2001 and 2005.

Figure 1.5 U.S. commercial airport operations (x million), forecast and realization, according to FAA terminal area forecast reports, between 1997 and 2006.



More accurate forecasts can be noticed in the enplanements comparison. Moreover, the trend is more suggestive than for the previous commercial operations. As illustrated in figure 1.6, the effects of the 2001 events have faded away, starting with 2005. However, a small increasing rate can be noticed from 2005 to 2006.

Figure 1.6 U.S. enplanement forecast and realization (x million), according to FAA terminal area forecast reports, between 1997 and 2006.



However, it should be borne in mind that by increasing the traffic volume without reducing the accident probability per flight would increase the overall number of flight accidents. Therefore, any new technology or procedure should be analyzed for its impact on volume and on risk. This is possible with a system level risk model. If historical trends continue, this growth in volume must be accompanied with a *decrease* in the accident rate per flight which is at least as great, preferably greater. Hence, designing for increased volume must be coupled with designing for decreasing risk.

Given the already very low accident rate for commercial aviation, together with the very high complexity of the total civil aviation system, many responsible agencies have concluded that further improvements in safety would be served by a comprehensive system-wide risk model for civil aviation. This model should enable the disaggregation of fatal accidents into their causal components, including, in particular, human error. The Dutch Ministry of Transport has therefore commissioned a Causal Model for Air Transport Safety (CATS) whose first phase of development is nearing completion.

This study represents an attempt to use the CATS safety model to quantify the risk impact of new Merging and Spacing (M&S) protocols. In line with the above discussion, designing systems for greater volume must go hand in hand with designing for lower risk. System level risk models allow total risk to be engineered rather than just undergone.

1.2. Thesis outline

Chapter 2 describes the Merging and Spacing (M&S) concept, its operational procedures and implied technologies, as well as relevant studies.

In Chapter 3, the Causal Model for Air Transport Safety (CATS) will be presented. The constituent elements will be described and the reasoning behind particular choices will be provided.

Chapter 4 describes the implementation of M&S protocols within the CATS model. The overall assumptions will be overviewed and the risk benefits and penalties will be identified. At last, the changes applied to CATS will be presented.

In Chapter 5, the numerical results will be presented. Three case scenarios will be provided, with respect to implied changes and corresponding traffic densities.

Possible future extensions implied by the forecasted traffic growth will be considered in Chapter 6.

Finally, Chapter 7 presents relevant conclusions and recommendations.

2. Airborne Precision Spacing in Merging Arrival Streams (M&S)

2.1. Introduction

Extensive research over the past 30 years by National Aeronautics and Space Administration (NASA), Federal Aviation Administration (FAA) and Eurocontrol has been conducted to increase the capacity of current runways, via precise spacing at the runway threshold and self-spacing of the aircraft. In the Advanced Air Transportation Technologies (AATT) Project, NASA and National Aerospace Laboratory of The Netherlands (NLR) have collaborated to explore the feasibility of the Distributed Air/Ground Traffic Management (DAG-TM). DAG-TM develops new terminal area procedures for both airborne and ground-based concepts to increase the traffic capacity. Advanced ground-based decision support tools and associated procedures are being developed at the NASA Ames Research Center. At the NASA Langley Research Center, the AATT project is exploring airborne technologies and procedures that will assist the flight crew in achieving precise spacing behind another aircraft. The concept of operations development began with an in-trail precision spacing study, continued with precision spacing in merging arrival streams and culminated with the limited use of maneuvering, which ensures a properly spaced arrival at the runway threshold.

An on-board guidance system, called Airborne Merging and Spacing for Terminal Arrivals (AMSTAR), will help the flight crew to follow the received spacing clearance from ATC. AMSTAR receives Automatic Dependent Surveillance-Broadcast (ADS-B) reports from the leading aircraft, own aircraft state data as well as wind data and computes the appropriate speed the aircraft has to follow in order to achieve the desired spacing interval at the runway threshold. Large improvements in system capacity, flexibility and efficiency, would be enabled by sharing information related to flight intent and traffic, and by collaborative decision making with distributed decision authority. The distribution of the decision-making authority implied that each aircraft contributes actively to the traffic management; this was seen as a possible key to increase traffic capacity by minimizing the occurrence of human workload bottlenecks.

2.2. The Development of Airborne Precision Spacing Concept

Under the sponsorship of AATT, NASA Langley Research Center, NASA Ames Research Center and National Aerospace Laboratory of the Netherlands (NLR) collaborated to explore the feasibility of the DAG-TM concept. Two of the fifteen DAG-TM concepts focused on the “free flight” approach, where the flight crew has independent authority to perform tasks currently associated with an air traffic controller, i.e. the flight crew has the capability and authority to self-separate from other aircraft by adjusting their self-selected trajectories and speeds. The concepts implied that, in addition to autonomous airborne capabilities for separation, ground-based decision support tools will also be used to resolve tactical conflicts and to manage traffic flows in congested airspace. Langley Research Center and NLR investigated the range of capabilities with respect to the two DAG-TM concepts, during cruise and arrival phase of flight. Langley primarily investigated issues concerning advanced airborne technologies, whereas the NLR explored technologies and procedures that would require minimum changes to flight deck systems and communication, navigation and surveillance infrastructure. The communication, navigation and surveillance (CNS) capability employed in tactical free flight operations was Automatic Dependent Surveillance-Broadcast (ADS-B). ADS-B provided, at a minimum, aircraft state data at intervals on the order of one second.

Beside en-route strategic airborne operations, capacity-constrained terminal area operations were also investigated. The inherent dynamics and highly constrained nature of terminal area operations requires another approach from that employed for the en-route flight phase, especially if maximization of airport throughput dominates other operational needs. A reduction in spacing buffers and hence higher throughput can be achieved by increased precision, which cannot be realized by a ground-based controller, as he must simultaneously manage numerous aircraft. Also, increased positioning capability provided by a limited maneuvering authority of the flight crew results in fewer missed approaches over time. As for the en-route operations, the ADS-B system is assumed for the terminal area research and additional information as planned final approach speed, wind data and intent information may be required, depending on the mode of operation. Distributed air/ground involves three operational modes: in-trail spacing, merging with converging traffic streams and maneuvering within prescribed corridors for optimal spacing.

It should be noted that, in each of the three operational modes, the following aircraft will maintain a time-based rather than a distance-based spacing interval from the preceding aircraft. Time-based spacing could have operational benefits as it may allow air traffic controllers to give spacing instructions to aircraft at high altitude that also remain applicable throughout the descent down to the final approach. Moreover, limiting constraints such as runway occupancy, wake vortex separations and human reactions are more naturally expressed in terms of time rather than distance and therefore more compatible with a time based spacing instructions. The fixed spacing interval concept is easy to understand and implement. Each aircraft maintains a fixed (time-based) distance behind the aircraft it is following. However, when considering multiple aircraft in-trail, the concept implies speed reductions performed at distances continually further from the airport which may result in increased aircraft fuel consumption and higher generated noise. On the other hand, traditional air traffic control operations successfully use fixed spacing interval concept by reducing the space interval as the in-trail speed is being reduced.

Therefore, for the in-trail spacing mode, the spacing clearance issued by the air traffic controller is time-based and accounts for different final approach speeds and wind environments. The aircraft follows the same flight path as the aircraft immediately preceding it, following the ground track of the lead aircraft (flight path history), which is provided on an onboard display. In-trail spacing can be applied at any point in the terminal area and it should be applied as far in advance as possible, in order to maximize the throughput. In-trail spacing may also have applications in the en-route and oceanic domains. The concept of operations of the in-trail spacing mode includes the use of an airborne decision support tool, consisting of a specialized algorithm, referred to as Advanced Terminal Area Approach Spacing (ATAAS) and a crew interface provided by supporting displays. This algorithm provides speed guidance in order to achieve a desired spacing interval at the runway threshold, which has been refined using extensive Monte Carlo analysis. The Monte Carlo simulation software was developed at MITRE Corporation; simulation details can be found in [30].

A nominal speed profile is included as part of a charted arrival procedure; it reflects speeds typically used in arrival operations. The charted arrival procedure can be used by all arriving aircraft in order to follow the nominal speed schedule, regardless of their ability to perform an approach spacing operation. As the main goal is to provide maximum achievable throughput in a stable and acceptable manner, the ATAAS speed guidance is limited to ±10% of the nominal speed profile so that system stability and pilot acceptability are maintained.

The crew interface included a cockpit display of traffic information (CDTI) to monitor the traffic and a Navigation Display (ND).The approach spacing elements of a B757 Navigation Display consist of the ownship, the ownship spacing position, the lead aircraft and the lead aircraft history track, which shows the ground track taken by that aircraft. The display also shows a data block containing currently entered ATAAS data and lead aircraft range.

A piloted simulation study conducted in January 2002 validated the results of the Monte Carlo analysis and evaluated pilot workload and acceptability. The study was conducted in a full mission B757 simulator with B757-rated airline pilots. The pilots were issued a clearance to follow the ATAAS speeds, allowing them to fly the predefined path through the terminal area while adhering to speed guidance provided by the ATAAS algorithm. The arrivals were flown using one of the three speed management modes: ATAAS coupled auto throttles, pilot control of speed though the mode control panel (MCP) and manual throttle control. The data collected in the study included aircraft state data, questionnaire data, workload ratings using the NASA-TLX (Task Load Index) method and eye-tracker data. Further details can be found in [37]. The aircraft delivery performance at the runway threshold was ±1 second for the ATAAS-coupled auto throttles and within 5 seconds for the other two speed management modes. The resulting times correspond to a threshold crossing accuracy of ±200 feet for the auto throttle-coupled mode and within 1100 feet for manual modes. The subjective data also yielded positive results, with high positive ratings from the pilots regarding overall acceptability, amount of head-downs time, and confidence in the guidance. Eye tracker data indicated minimal changes in scan pattern and no significant increase in heads-down time as a result of using the ATAAS tool. In order to validate the results of the simulator study in an operational environment, a flight activity involving three aircraft of different performance characteristics also had to fly the approach spacing concept.

Aircraft arriving on different routes that merge with appropriate spacing at a common point are considered for the merging operations. These define the second developed operational mode and will constitute the subject of this report. The required time of arrival is either assigned or computer based on the lead aircraft's estimated time of arrival at the point. The mode assumes that a pre-definite route environment exists to allow aircraft to arrive properly spaced at the merge point. Merging operations were investigated through algorithm and display modifications to support the capability to meet the assigned spacing clearances.

Unlike the two previous operational modes, where the crew decision capabilities are the speed adjustments alone, in the maneuvering mode the aircraft are given the flexibility to define their own routes within prescribed airspace. However, this implies advanced planning, prior to terminal area entry that results in an optimized, stable flight path through the terminal area. As suggested in [27], assuming an adequate conflict detection capability is available, more dynamic maneuvers could also be executed. Maneuvering operations in the terminal area implies additional work in several areas, including flight crew information requirements, aircraft equipment requirements and procedures. Nonetheless, it is anticipated that the existing research and development for the en-route domain will be used in developing a maneuvering capability.

With respect to feasibility, research and development provide strong evidence that free flight operations in capacity-constrained terminal arrivals are feasible and provide benefits. In-trail spacing operations can be performed under real-world conditions with minimal impacts to crew workload. Among the benefits that have been identified in both safety and efficiency, it is worth mentioning that flight deck alerting of predicted separation violations, generated by airborne algorithms, can augment those provided by traffic controllers. In addition, safer operations can result from less radio frequency congestion and from a mitigation of errors based on a redistribution of workload between flight crews and controllers.

The completed research of the DAG-TM concept elements demonstrated that airborne autonomous operations can be reliably performed without controller intervention in the en-route domain and that the airborne separation assurance in terminal arrival environment is feasible, but would involve limited delegation of responsibility by the air traffic service provider and require more sophisticated airborne tools than those used for the in-trail spacing operations. It is noteworthy that, with increased air traffic, the concept would need to accommodate a wide range of airborne capability within many operating environments. Future research focused on the simulation of DAG-TM air and ground components through interconnected traffic simulation laboratories at Langley, Ames and NLR. The Ames laboratory simulated the ground-based components of the concept, including air traffic service provider and aeronautical operational control, while Langley and NLR laboratories simulated the airborne components. Monte Carlo analyses were also planned to further investigate safety and the impacts of reducing current separation standards. Moreover human-in-the-loop experiments and full-mission flight simulations were used to develop multi-crew procedures and evaluate crew workload.

Eurocontrol Experimental Center, through the European Organization for the Safety of Air Navigation, also extensively investigated the use of airborne spacing in the terminal area, in which the flight crew is tasked to maintain the spacing to a preceding aircraft. It was assumed that air traffic controllers retain the responsibility for keeping aircraft separated but can, when appropriate, delegate pair-wise spacing related tasks to the flight crew. As in the aforementioned studies, information to support these tasks, such as identification, position and airspeed of the other aircraft, could be transmitted by the air-to-air surveillance system ADS-B. Unlike previous experiments that assumed similar aircraft performance and simple constant wind models, the fast time simulations performed at Eurocontrol, [6][7], focused on comparing approximate and exact time based spacing and on using exact time based spacing to investigate the effects of a combination of mixed aircraft types and more realistic wind conditions on spacing performance. The spacing performance when using an approximate time-based spacing criterion based on current lead aircraft speed was compared to an exact time delay spacing criterion based on lead aircraft position history. The exact time-based spacing resulted in smaller time delay spacing errors and smoother airspeed behavior. Hence, the exact time-based spacing of 60 seconds was then used to compare the spacing performance of a heavy aircraft (a Boeing 747) following a light aircraft (a Fokker 100) with a heavy aircraft following a heavy aircraft for different wind conditions. The results showed that a heavy aircraft flying the first scenario encountered approximately 40% more time spacing error than the one flying the second scenario. For the different wind conditions effects, it was found that the spacing error increased slightly with constant wind speed but always remained within 10 seconds, for different wind speeds and different altitudes. The average speed was altitude dependent and the wind model was based on the joint aviation requirements all weather operations certification process. Turbulent winds and particularly cross winds severely degraded the operation's stability, as cross winds perturbed the track guidance.

2.3. Concept of Operations and Flight Crew Procedures

The Merging and Spacing concept development is being conducted by NASA, Federal Aviation Administration (FAA), MITRE, UPS, Aviation and Communication Surveillance Systems (ACSS) and Eurocontrol. The concept is designed to merge arriving aircraft from different altitudes and directions from the en-route flight phase and deliver that arrival stream precisely to the runway threshold using optimized flight profiles within minimal speed changes. The air traffic controller delegates responsibility for achieving precise spacing at the runway threshold to the aircraft flight crew and retains responsibility for separation and for issuing spacing requirements to the flight crew. The airborne technology, AMSTAR, uses ADS-B and aircraft state data, final approach speeds and wind data to compute speed commands for the AMSTAR equipped aircraft to follow. The concept accommodates equipped aircraft, using self-spacing procedures, as well as unequipped aircraft, using present-day instrument flight rules, within an arrival stream. As long as the unequipped aircraft, or a ground-based system, broadcast the appropriate data, they can serve as the lead aircraft for an AMSTAR-equipped aircraft. Hence, the AMSTAR technology would permit time-based spacing between any two aircraft heading for the same runway, even if they are not yet physically in-trail. This situation occurs if aircraft entered the terminal area through different entry points or were separated on to different approach routes to the runway for performance reasons.

The Merging and Spacing concept employs ground and airborne tools as well as related procedures to meet the need of predicted increased airspace capacity, by providing an increase in runway throughput capacity and a reduction in arrival aircraft delay. The ground based tool assists the Air Traffic Control (ATC) in issuing arrival times at the runway threshold, considering the aircraft current position and speed. Further adjustments can be made when considering runway throughput constraints such as weather or wake vortex separation criteria. The appropriate speed required is computed close to the minimum time or distance allowed for the runway conditions. A separation buffer is added to the computed interval to reduce the likelihood that the instrument flight rules criteria will be compromised or that the aircraft will have to execute a missed approach because of insufficient spacing. Past research indicates that the buffer is approximately 20 to 30 seconds [32]. The desired spacing clearance at the runaway threshold is translated back in time and space, to an en-route metering fix at a certain altitude.

The concept extended previous research elements from the in-trail precision spacing, by combining and refining, among others, the use of the airborne technology for the speed guidance, the use of broadcast aircraft state data to correct forecasted wind errors and runway estimated time of arrival calculations and the establishment of the desired spacing interval between aircraft during the en-route phase of flight [31]. Following the success of the aforementioned ATAAS flight tests, it was decided to extend the technology capabilities to include merging arrival streams. This will allow an earlier issued spacing clearance, therefore more time to achieve the assigned spacing. The ATAAS tool was expanded to provide spacing guidance prior to merging behind a lead aircraft and renamed AMSTAR (Airborne

Merging and Spacing for Terminal Arrivals). As with ATAAS, the aircraft will follow a charted Standard Terminal Arrival Route (STAR), similar to those used in current operations, but extended to include a complete lateral path to the runway, a vertical path and a speed profile, so that intent information is easily known. Including the nominal routing and speed profile as part of charted arrival would allow an aircraft to be cleared for this arrival. The nominal speed profile associated with this charted procedure provides a basis around which AMSTAR will generate the speed commands to be used by the flight crew.

The basic system procedure is the issuance of a clearance from the air traffic controller to the AMSTAR-equipped aircraft flight crew, which identifies the traffic to follow, the route to fly and the assigned spacing interval. This clearance could be issued at any time after entry into the terminal area. Once the flight crew accepts the spacing clearance and starts following AMSTAR speed guidance, no further speed clearances are needed from the air traffic service provider; however, other communications as approach and landing clearances take place as expected.

The calculation of the projected spacing interval was changed from a time-history approach to a trajectory-based approach. Knowing the arrival route assigned to the ownship and that assigned to the designated lead, via ADS-B, AMSTAR computes the expected time of arrival (ETA), at the runway threshold, for both the ownship and the assigned leading aircraft, if the final approach speeds are available. AMSTAR uses the time differences as input to the speed control law, which remains unmodified from ATAAS, and computes any required speed change relative to the profile speeds being flown. The resulted speed-to-fly is displayed on the flight deck and, optionally, used as speed guidance input to the operating auto flight system, which gradually reduces the error in the assigned arrival spacing, while ensuring safe and stable ownship merging behind the lead aircraft.

The goal of the merging and spacing concept is to achieve a system-wide performance improvement focusing on precisely spacing the aircraft in a stream and not just on a single pair of aircraft. Beside the increased runway throughput, the merging and spacing concept has a remarkable potential, by enabling the use of a Continuous Descent Approach (CDA), to reduce fuel consumption and noise.

A recent upgrade of AMSTAR, called ASTAR (Airborne Spacing for Terminal Areas) included the improvement of the trajectory prediction, ETA calculations and of the internal wind model to accept real-time updates and to enable operations to start at cruise altitudes. Spacing at cruise altitudes would enable merging in an en-route flight phase as well as continuous descent approaches (CDA). However, the concept of operations and the flight crew procedures detailed further will refer to AMSTAR technology.

The AMSTAR software is designed to provide pilots with speed guidance which, when properly followed, will result in the target spacing interval behind the lead aircraft at the runway threshold. Supporting pilot interface and display elements provide information on the mode of operation and the state of the aircraft relative to the lead aircraft. To achieve the concept goals for the system-wide efficiency, AMSTAR was developed with features and limits on the speed guidance it provides. Commanded speed will not exceed 10% of nominal, charted, speed for any given segment on the arrival. Speed commands are also limited to prevent exceeding flap and landing gears limits.

Compared to ATAAS operations, additional information is required from the leading aircraft in AMSTAR operations, namely the arrival route being flown by the lead aircraft. Beside the arrival route, each aircraft would broadcast its final approach speed and weight/wake-vortex class. AMSTAR-equipped aircraft will transmit the ID of its lead and the assigned spacing, as well as information regarding the AMSTAR operational mode. This information could provide data for conformance monitoring and error checking to ground-based systems. Given the combination of high traffic and large distances between different entry points at typical terminal areas, the AMSTAR tool is designed to accept pilot input lead aircraft data as well as assigned spacing interval and to fly the charted speed profile, while waiting to acquire the ADS-B transmission from the leading aircraft. This is called a "profile" mode. The profile mode can also be assigned by the air traffic service provider, when there is no lead aircraft to follow. If the lead is not acquired within a pre-specified time interval, the tool will advise the pilot of this fact. As soon as the lead is acquired through the data-link, the tool transitions into a "paired" mode, when it begins the actively spacing relative to the lead. As the current operational considerations imply a stabilized speed prior to touchdown, AMSTAR also transitions into a "final" mode, once the aircraft has crossed the Final Approach Fix, which is 7 to 4 miles from the runway.

Flight crew procedures and cockpit interfaces have been prototyped with the overall objective of supporting crew interaction with AMSTAR tool without increasing workload. Prototypes of the airborne tool, flight deck displays and pilot interfaces have been implemented in a medium-fidelity aircraft simulation housed at NASA Langley's Air Traffic Operations Laboratory (ATOL), [23][24][32], where piloted simulations have been tested and evaluated. Relevant results of the human-in-the-loop experiments will be presented in a subsequent section.

Since the crew procedures are largely unchanged from those employed by ATAAS, the displays are very similar to those used for the in-trail studies. The major changes are an advanced set of advisories and announcements on the engine indicating and crew alerting system and changes to conform to the Boeing 777-like cockpit displays used in ATOL. As part of this integration, a new speed guidance mode was created called Pair Dependent Speed (PDS). If the pilot chooses this mode, the source of speed guidance becomes the AMSTAR tool. A full description of the displays can be found in [23].

Supporting display elements as Primary Flight Display and Navigation Display provide information on the mode of operation and the current state of the aircraft relative to the leading aircraft. A trail of "history dots", on the navigation display, the ground track of the lead aircraft and can be used instead of an area navigation (RNAV) route for lateral navigation. In order to allow the flight crew to select the lead aircraft and enter other appropriate data, a simple pilot interface with the AMSTAR tool, similar to the ATAAS interface, was provided via two custom Control Display Unit (CDU) pages. The CDU pages allowed for inputs to the AMSTAR tool, i.e. the reference aircraft and the followed trajectory as well as the assigned spacing interval. The pilot could select the referenced aircraft from a list of all aircraft within ADS-B range. Once the reference aircraft is selected, the spacing interval would be entered by the pilot. If the reference aircraft is found, AMSTAR would go into an armed mode; otherwise, the tool would go into profile mode until the referenced aircraft was located. If five minutes pass and the reference aircraft was not located, the pilot would be alerted. Further checking if correct aircraft was selected would be performed, followed by an ATC contact for supplementary instructions. In a pair mode AMSTAR operation, the tool receives enough information on the lead aircraft to compute the projected spacing at the runway threshold and then offer speed guidance to the crew to meet the assigned spacing. The third mode is called "final" and occurs when AMSTAR stops guiding based on the lead aircraft or the profile and slows the aircraft to its programmed final approach speed. Even though t remains engaged for the final approach, AMSTAR does not provide active spacing guidance inside the final approach fix.

AMSTAR mode and guidance information were placed on the Primary Flight Display for a human-in-the-loop experiment simulated at Langley Research Center [36], although alternative locations have been considered for near-term implementations. AMSTAR status and mode information appear as a small text block in the upper right corner of the display. The text is white for armed and green for active. The text shows the current mode (PROF, PAIR, FINAL) and the current speed target. When AMSTAR is the active speed guidance source, the speed target and bug on the speed tape are green. A new mode control button, placed on the mode control pilot is available to enable AMSTAR operations. This new speed guidance mode was called pair-dependent speed (PDS).

The navigation display was used to show traffic information and provide situation awareness for the spacing operation. The reference aircraft is highlighted with a green outline. In the middle of the left side of the navigation display, a small text block shows the callsign of the reference aircraft and their slant distance range. At a small enough map range settings, a series of history dots appear behind the reference aircraft; they show the lateral path flown by the lead aircraft, particularly useful for a "follow the leader" operation. Another addition to the navigation display was a spacing position indicator that showed where AMSTAR was guiding the aircraft to. The pilots were instructed to follow the speed guidance presented on the primary flight display and use the navigation display information only for situation awareness.

Moreover, alert messages are available to notify the crew of abnormal or unexpected events during the spacing operations. The most common and relevant for the performed experiment was a "PDS DRAG REQUIRED" message, which appeared when the aircraft was more than 5 knots above the commanded speed or more than 400 ft above the vertical profile. In those circumstances, the use of the speed brakes was required to regain the speed and the vertical path. This generally occurred when the aircraft was descending near idle thrust and a speed reduction was required.

Summing up, the AMSTAR tool is initialized by crew input of controller provided spacing information and then provides speed commands to obtain a desired runway threshold crossing time, relative to the lead; it compensates for actual final approach speeds of own and lead aircraft and it respects wake vortex minima requirements as well as provides guidance for a stable final approach speed. Its robustness to a variety of operational variables, such as wind prediction errors, ADS-B range limits, meter-fix arrival time errors and variation of aircraft type were evaluated. Some of the results of these fast-simulation studies will be presented in the following section.

2.4. Fast – Time Study Experiments

In order to evaluate the performance of AMSTAR, a simulation environment, which enables fast-time studies of AMSTAR operations, has been developed. Fast-time simulation is a particularly cost-effective method in which procedures are evaluated before expensive real-time simulation is carried out, new procedures are implemented or new operations or structures are set up. The simulation tool developed was called the traffic manager experiment (TMX), which is a multiple-aircraft desktop simulation program created by NLR. The integration of the AMSTAR algorithm into TMX and improvements added to TMX to support fast-studies AMSTAR studies, as well as simulation results will be presented further.

The fast-time AMSTAR simulations were designed to study wind prediction inaccuracies, mixed aircraft classes in the arrival stream, data broadcast range limitations and Terminal Radar Approach Control (TRACON) entry time errors. The results were used to identify the range of conditions under which AMSTAR can operate, but also to investigate the speed guidance algorithm performances.

The TMX traffic manager represents an important element for air traffic management research, both at NLR and NASA Langley Research Center. Used as a stand-alone air traffic simulator, TMX can operate in real-time or in fast-time, accepting as user input both predefined scenario files, which contain time-stamped commands to create, control and delete aircraft throughout a scenario and a graphical user interface. The user interface contains, among others, a radar-like traffic window and a command/message window.

AMSTAR is integrated into the TMX auto throttle module, incorporating PDS as an additional speed guidance mode. As the auto throttle module is itself a subset of the lateral/vertical navigation module, PDS can only be engaged when a TMX aircraft is flying fully coupled to it s flight management system route. When uncoupled, TMX uses a procedural mode, based on the aircraft type, configuration and altitude. The AMSTAR code base in TMX is identical to that used in Langley's higher-fidelity flight simulations. However, the interface was modified to allow up to 50 simultaneously AMSTAR arrivals in TMX, instead of the original design for a single aircraft. The AMSTAR module input information consists of:

- Command Data, i.e. lead aircraft and spacing interval;
- Traffic Data, containing state, route, final approach speed and weight class;
- Ownship Data, containing state, route, final approach speed and weight class;
- Environment Data, i.e. airport elevation and approach winds;
- Time Data, containing current time and increment.

As the command data would normally be input by the pilot based on ATC clearances, in the simulation environment the data is input via user interface commands, scenario commands or default values in TMX. To increase the fidelity of the models, additional logic has been included in the TMX to determine the phase of flight, aircraft configuration and consequently, aircraft performance. This logic is based on current airspeed, target airspeed, current altitude, target altitude and vertical speed. A full description of specific procedures can be found in [34] and [35].

In order to support studies of the range limitations on AMSTAR performance, a more realistic ADS-B message reception model was assumed. Previously, TMX used a deterministic ADS-B reception model with a single maximum distance parameter. For two aircraft within this maximum distance, the ADS-B messages were always received, whereas for two aircraft outside this maximum distance, messages were never received. The improved ADS-B model used for the traffic manager environment depicts message reception behavior near the range limit more accurately. An arrival sequencer/scheduler has been added to TMX to properly assign lead aircraft and spacing intervals to AMSTAR arrivals. The aircraft sequences are based upon the estimated time of arrival at the runway threshold.

To demonstrate the enhancements to TMX discussed above, the results of a simulation of multiple AMSTAR arrivals flying multiple routes to a single runway will be described. The fast-time simulation study was designed to gain insight into the performance of AMSTAR under nominal variations in certain operation conditions, as winds and wind prediction errors, ADS-B range, mixed aircraft types, variations in actual times of arrival at the Terminal Radar

Approach Control (TRACON) boundary and the frequency of merges within the arrival streams. The operational ranges considered in the study are presented in the table below.

The nominal conditions considered are 80 NM for ADS-B range, 5 seconds for RTA error, a mean direction wind prediction error of 20 °, diverse mix of aircraft types and a merge complexity of 1 arrival per merging operation. The nominal truth wind field ranged from 10 knots/155° at sea level to 40 knots/170 ° at 15000 feet. Each test condition was defined by maintaining nominal values for all parameters except the variable at interest. However, for the evaluation of the effects of wind-prediction errors, an extra truth wind-field condition was also tested.

The airspace modeled for the study was Dallas Fort-Worth (DFW) TRACON, consisting in a symmetric four-corner post airspace. Three standardized arrival routes were designed for the use in AMSTAR operations. It was assumed that all aircraft were AMSTAR-equipped. The required time of arrival errors for each aircraft were randomly selected from a normal distribution and each test condition was repeated 40 times. Only the RTA errors were re-sampled in the repeated scenarios; aircraft type sequence and arrival route sequence were not varied.

In each scenario, a sequence of one hundred aircraft entered the terminal area through one of the three arrival routes at the runway 18R at DFW, where every arrival encountered a single merge condition on route to the runway form the meter fix. The long arrival streams were modeled to detect any undesirable behaviors resulting form the AMSTAR extended operations. The aircraft types in the arrival stream were randomly selected from a pre-defined list. When considering a mixed type of aircraft, the spacing interval assigned to each arrival depended upon the wake-vortex category of the aircraft and that of its lead. The current distance-based wake-vortex minima were transformed into time-based minima, using representative final approach speeds for each category, to compute the time-based spacing required between arrivals.

Initial analysis of the data focused primarily on the precision with which the assigned spacing was achieved at the runway threshold. The difference between scheduled and actual crossing times for each aircraft, as well as the difference between actual spacing and assigned spacing was examined. A monotonic decrease in the spacing error could be noticed, as the goal of the concept is to reduce the spacing error at the runway threshold and not to aggressively achieve and maintain the assigned spacing. The spacing errors resulted from each of the aircraft in the arrival stream, for a single scenario of the nominal test conditions were within ±5 seconds [34]. Moreover, the magnitude of the schedule deviation never exceeds 30 seconds.

AMSTAR technology is designed to achieve spacing precisions using speed changes. As frequent speed changes could lead to downstream instabilities and comfort issues, the system implies a gradually minimization of the spacing error, by limiting the deviations from the reference speed profile. Therefore, speed profiles commanded by AMSTAR were compared to the standard profile. Fast-time simulations showed that AMSTAR operations added six speed changes to the basic five of the arrival route. Also, as the number of speed changes required for precision spacing generally does not increase with position in the landing sequence, the stream stability is not affected by the merging and spacing concept.

All the above results reflected a typical scenario under nominal test conditions. Averaged spacing errors for each aircraft in the stream indicate that individual spacing errors remain bounded within ±10 seconds. AMSTAR tool achieves a schedule deviation of no more than 30 seconds over three hours of simulated operations under nominal test conditions. The histogram of spacing errors averaged by aircraft category, rather than position in the stream, suggests that "small" aircraft generally experienced a larger spread in spacing errors, although the mean error is comparable to those of other categories. Moreover, it has been observed that aircraft following a "small" aircraft generally experienced higher spacing errors than aircraft from other categories and that aircraft experiencing the highest spacing errors for the nominal test condition were all following "small" aircraft. Further underway analysis will determine the causes for this behavior.

Data was also collected for an arrival stream composed entirely of a single type of aircraft and compared to a diverse stream, with all other test variables maintained the same as the nominal test conditions. Simulations indicate that aircraft in a homogenous stream experienced a much smaller range of spacing errors than in the diverse stream. With respect to the average number of speed changes, further analysis indicates that the higher speed changes counts are associated with aircraft from southwest, landing behind an aircraft from the northwest entry fix. This behavior is completely absent in the more realistic case of a diversified type of arrivals and the causes of this effect are still being investigated.

ADS-B range effect on spacing performance was also studied, as this range can be particularly small within a busy terminal environment where there a high number of broadcast signals (ADS-B, secondary surveillance radar, traffic alert and collision avoidance systems). Even though limiting the reception range from a more realistic 90 NM to 30 NM had little impact on the mean and standard deviation of the overall performance (from -0.13±3.42 to -0.2±4.03), the second reception range introduced more outliers. The extreme values result from a situation when the aircraft approach their merging point from opposite sides of the airfield and there is a significant spacing deviation that needs to be overcome. Recent refinement of the ADS-B technology enables, though, a range of 90 NM, which covers the extent of most terminal areas.

Wind forecasting errors proved to be the most disruptive effect, mainly because the wind forecast is used in computing the expected time of arrival at the runway threshold. The differences between the aircraft's forecast and the truth winds, both in magnitude and direction, were considered for the simulation studies. The baseline scenario assumed an accurate forecast. With respect to directional errors, an accurate magnitude was assumed, but directional errors of 5º and 20º off the truth winds. For the magnitude errors an accurate direction was assumed, but -10 knots and +40 knots mean error. The wind field varied in both direction and magnitude with altitude. Except the +40 knots mean error case, when the traffic flow was seriously disrupted, all studied scenarios provided acceptable spacing performances.

The proper scheduling and delivering of the aircraft at the starting point of the spacing operation, so that the aircraft is able to compensate for the spacing deviations and uncertainties that occur during the remainder of the flight is termed preconditioning. As the spacing aircraft can use only speed changes to control the spacing interval relative to the lead aircraft, the preconditioning requirement would be lessened if the aircraft were able to make route adjustments as part of the spacing operations. A ±15 seconds and ±60 seconds scenarios were studied as spacing deviations based on preconditioning. Again, small differences encountered with respect to obtained mean and standard deviation, but the large number of outliers suggested that a delivery precision of less than 60 seconds is needed. The largest spacing deviations were encountered by aircraft arriving along the shortest arrival route with a large initial spacing deviation and also aircraft following this aircraft. Initial spacing deviations of more than 60 seconds create the possibility of re-sequencing the merging arrival streams, as the spacing intervals were generally between 90 and 150 seconds.

A fast-time study also tested the benefits of knowing the final approach (FAS) speed of the leading aircraft. Four situations were compared: the lead final (FAS) approach speed was known, the lead's FAS was assumed to be the same of the ownship, the lead's FAS was assumed to be a generic value based on a wake category and the lead's FAS was assumed to be a generic value of 130 knots regardless of wake category. The assumed ownship FAS was the planned FAS. The results show a significant performance benefit in threshold spacing for knowing the lead's FAS. The worst results were obtained when assuming the same FAS for the leading aircraft as the ownship FAS. The other two tested conditions, considering a wake category based assumed FAS and a generic value of 130 knots registered similar results.

2.5. Evaluation of the Concept in a Human-in-the-Loop Simulation

Human-in-the-loop simulations and flight testing are necessary for the evaluation of multiple aspects of the AMSTAR system, such as flight crew acceptability, ATC acceptability and operator workload, as well as the feasibility of using traffic information displayed on the flight deck to enable airborne-managed spacing. An experiment to test the flexibility of Airborne Precision Spacing operations under a variety of operational conditions was recently performed at the NASA Langley ATOL [25] [36]. The operational conditions included several types of merging operations and approach geometries along with complementary merging and in-trail operations. Twelve airline pilots and four air traffic controllers participated in this simulation and performance and questionnaire data were collected from a total of 72 individual arrivals.

Given the diversity of the airports arrival architecture, it is important that the airborne technology and associated procedures are designed with the minimum site specifications and readily adaptable to a wide variety of route designs. Therefore, an experiment that would investigate the flexibility of the concept tools and associated procedures to a variety of realistic arrival routes and merging geometries was designed. Based on a range of merging angles, distances of the merging point to the final approach fix (FAF), angles of the descent path from TRACON entry and lengths to the final approach path examinations, several representative, high-demand US airports were simulated for this experiment. The airspaces used were Northern California (NorCal) TRACON, Chicago TRACON and New York TRACON with traffic arriving at LaGuardia. The experiment design is fully described in [25].

All considered arrival routes were based on published standard terminal arrival routes or area navigation procedures, extended to intercept the instrument flight course. For the purpose of the study, an extension of the current arrival procedures was used, which were connected with approach procedures to create a continuous route from TRACON entry to the runway. Where necessary, input was sought from pilots familiar with the specific airspace operations. However, in Chicago airspace simulation, a new waypoint had to be created, as there was not an existing waypoint where the turn from inbound to downwind legs for one of the routes. All altitude crossing restrictions and, where available, speed reduction points were based on published procedures. In all scenarios, the aircraft started the simulation of operations just outside the TRACON entry point.

The first selected type of airspace was Chicago O'Hare. The selected geometry consisted of a standard entry leg leading to a downwind leg. The second route merges at either the turn to base or turn to final. The aircraft turns on to the final approach course approximately 15 miles from the runway threshold. Two arrival routes were considered for the runway 22R, which cover approximately 60 NM from the starting point to the runway threshold. There is a 90º intercept angle between the two routes at the merging point.

A shallow intercept angle for two merging routes was chosen for the second considered arrival route geometry. The effect of this geometry is an extension of the merging region and also a reduction of the turn dynamics of the aircraft. Two arrivals from the south and southwest of New York going into LaGuardia's runway 4 represents a good example of this type of operation. Both chosen routes are approximately 60 NM long and one of the routes nearly follows a straight line. The merging intercept angle is approximately 30º and the merging point is at nearly 17 NM from the runway threshold.

The final considered geometry had a steep descent, which makes managing a deceleration at the same time difficult. Another point of interest was represented by a short combined final approach segment. With this respect, two arrival routes leading to runway 28R in San Francisco airspace are representative for the considered geometries. Based on the terrain and other air traffic considerations, the arriving aircraft are kept high until late in the arrival. Both routes encounter descents of between 7000 ft and 8000ft over a 22 NM path, which gives a flight path angle of 3º to 3.4º. During this time, the aircraft must also be decelerating from 250 knots to 170 knots that caused the pilots to actively manage their aircraft's drag. The two routes converge at about a 50º angle at the merging point and the spacing needed to be nearly achieved before the merging point.

All scenarios implied an included nominal wind field that was a constant 10 knots directed 10 degrees east from the runway alignment. The wind prediction errors were simulated using a predicted wind field of 12 knots and 20 degrees east of the runway alignment. An additional real-life uncertainty was included, by delivering the aircraft to the TRACON entry normally distributed around the scheduled time with a 15 second standard deviation.

The experiment was designed for 6 subjects and used the arrival airspace and type of operations, merging or in-trail as independent variables. The type of operations was introduced to observe whether there are any impacts on performance introduced by the extension to merging traffic. The procedures and the speed guidance algorithm for in-trail aircraft were nearly identical to previous ATAAS tool developments. A supplementary baseline run was performed, to separate out difficulties with the simulation environment from difficulties with the new procedures. Each scenario used six subject pilots, two subject controller and three confederate pilots, who were not flying for the evaluation session. One confederate pilot led the stream and flew the standard profile without any spacing clearance. The subject pilots were active line pilots from major commercial or cargo airlines with recent experience with Boeing glass cockpits. The controllers were active controller from a range of medium to hub-sized TRACONs. Two sessions were run, with a total of 12 subject pilots and four controllers involved.

The experiment was performed at NASA Langley's Air Traffic Operations Laboratory. The laboratory houses twelve medium-fidelity, workstation-based flight deck simulators, a high fidelity future communication navigation surveillance (CNS) infrastructure, a target generator and several low-fidelity controller workstations. The flight deck simulator, called ASTOR, models current basic aircraft components and include aircraft and engine models, autopilot and auto throttles system, flight management computer (FMC) and multi-function control display unit (MCDU), a mode control panel (MCP) and electronic flight instrument systems (EFIS) control panel, displays such as the primary flight display (PFD), navigation display (ND) and engine indication and crew alerting system displays (EICAS), sensor systems and the communications management unit (CMU). Current advanced technology components include representations of the future communication navigation surveillance, ADS-B, onboard systems that manage traffic information, flow constraint information and airspace constraint information.

The pilots were rated on a Boeing cockpit aircraft type such as 777, 767/757, 747-400 and 737. The majority had 757/767 experience and only one had 777 experience. The training included several practice runs, seven data runs and a debriefing session and several hands-on and practice sessions. The training session consisted of briefings on the concept of operations, the use of the ASTOR simulator and the use of AMSTAR and the pair-dependent speed mode. The pair dependent speed mode takes the AMSTAR speed guidance and supplies it to the autopilot systems, replacing the flight management computer when activated. The desktop simulator including mouse interactions, translations of physical knobs and dials to graphical representations were tested in the simulation environment. Special attention was paid to known differences between the ASTOR simulator and the behavior of the real aircraft such as vertical navigation modes, aerodynamic characteristics and flap deployment schedules. It is clear from the data analysis that either additional specific training was needed or only subjects with experience on the Boeing 777 should have been considered.

Beside the ASTOR training, the AMSTAR/PDS training introduced the pilot interfaces and display modifications as well as airborne precision spacing procedures. Possible failure models and alerts were presented along with the expected pilot response. Two practice runs were flown and all pilot training was performed in the Dallas Fort-Worth airspace, not to skew the pilots' performance in the data collection airspaces. The pilots were instructed to accept and follow all clearances given by the controllers, engage the AMSTAR tool and allow the speed guidance provided by AMSTAR. Afterwards they monitored the speed to ensure that the aircraft was properly configured for landing. The pilots' data run ended after crossing the runway threshold but before touchdown. The pilots could opt for either following the vertical path using the vertical navigation system or executing a flight level change, as they felt comfortable or as their individual company policies recommended. Objective performance data was collected for all aircraft and the pilots completed a questionnaire after each data run.

The controllers' responsibility was to assist in issuing the spacing clearances and evaluating the traffic behavior. A computer display was available for them to monitor the airspace sectors, the traffic and the active arrival routes. Displayed trend vectors were also available for each aircraft. The scripted sequence of aircraft, which resembled the paper scripts where the controllers could make notes, along with the expected arrival route were given to the controllers before each run. Two controller positions were defined: a feeder position that controlled the aircraft from the TRACON entry to close to the merging point and a final position that included the merge point and the final approach. For the realism of the spacing operations, a tower controller position was assigned to a confederate controller, who had no influence on the behavior of the pilots or controllers. The feeder controller would clear the arriving aircraft for the arrival route and then issue the precision spacing clearance. The clearances took the following form: "American 123, Cleared Position Spacing, Maintain One Two Zero Seconds Spacing, Reference Continental 321". This would clear American 123 to merge, if necessary, and space 120 seconds behind Continental 321. For the experiment design, all aircraft were spaced at 120 seconds, which corresponds to a minimum spacing distance that is slightly greater than the required wake vortex separation. As the aircraft approached the merging point, the feeder controller would hand them off to the final controller and issue a frequency change to the pilot. The final controller would issue a clearance for the instrument landing system approach as the aircraft neared the run on to the final course. Once established on the localizer and glideslope, the final controller would transfer the aircraft to the tower controller who would clear them to land.

Although the controllers were asked to monitor the traffic behavior and to observe the conformance and the safety of operations, they were asked not to intervene, as it allowed for a more rigorous data analysis. The subject controllers could mark an event on their screen and capture the current traffic position, which were later discussed with the pilots. In the same manner, the controllers responded to a questionnaire at the end of the data runs, but no performance data was collected or analyzed for the controllers. The experiment results consisted of three parts. First, the objective aircraft performance was analyzed then the performance observations were made during the data runs and while replaying the data. Third, the results of both the pilot and controller questionnaire were evaluated.

As the goal of the spacing operations is to precisely space aircraft across the runway threshold, the spacing interval was measured as the time difference between consecutive aircraft crossing the threshold. As mentioned earlier, all aircraft were assigned a spacing interval of 120 seconds. Also, the aircraft flew through a wind field that was inaccurately predicted and arrived at the entry point with a spread of times around the scheduled time.

Across all considered conditions, the measured spacing interarrival was 119.2±4.7 seconds (mean ± standard deviation). The standard deviation was larger than expected, based on previous ATAAS simulations, where the pilots were able to achieve precision of ±2 seconds. Nonetheless, much of this larger spread was attributed to flight deviations resulting from the pilots' understanding of ASTOR or pilots' unfamiliarity with 777 cockpit procedures. The experiment was designed to determine if the performance of spacing operations were affected by airspace design or type of operations performed. A three-way ANOVA found there were no statistical differences between airspace, operations or subject ($p>0.6$ for all cases). However, these three sources only accounted for 15% of the total observed variation. The experiment was not designed to uncover other sources of variation, although significantly variations were observed among runs by the same subject pilot.

Another concern of the spacing operations is the number of additional speed changes. For this, the number of the speeds commands issued by AMSTAR was counted. These were generally 5-10 knots speed changes, given the speed limitation imposed by AMSTAR. The speed changes associated with the standard terminal arrival route, of approximately 30-40 knots, were not included in the counting, yielding an average of 5.9±2.6, which are consistent with the previously mentioned results, from the fast-time simulations. An ANOVA test showed that the number of speed changes was not dependent on the arrival route, the type of operation of the subject ($p=0.16$, 0.79 and 0.98 respectively).

The final objective aircraft performance evaluation considered the overall behavior of a stream of aircraft. The running spacing errors, i.e. the differences between the predicted spacing at the threshold and the assigned spacing value, were never more than 25 seconds off and most of the times were 10 seconds or less.

Beside the analysis of recorded data, video playback of the pilots' actions and interactions with the simulator was analyzed. Several confounding effects were found in the experiment that can be attributed to pilot behavior and training that were unrelated to the spacing operations. Each pilot performed a baseline run, where he followed the flight management system path without any spacing operations. As many of the problems seen during the spacing operations also encountered during these baseline operations, this suggested that the cause was not the spacing operations or procedures, but other effects. It was found that 12% of the approaches resulted in either an unstable instrument approach or a flaps overspeed. For the baseline runs the error rate was 10% and once corrected for the airspace used for the baseline, the operational error rate was identical. While an overall primary cause could not be identified, the problems seemed to be related to poor understanding of Boeing 777 operational procedures, like flap speeds, and respective vertical navigation, pilots' unfamiliarity with "slam drunk" arrival procedures, poor understanding of energy management procedures, unrealistic flight deck cues, inadequate simulator or aircraft-specific training and single pilot operations in a traditional two-crew members environment.

As some of these causes are related to the fidelity of the simulation environment, it was suggested that similar studies need to be validated in higher fidelity simulations. Additional problems can be attributed to the pilot pool requirements and training. Half of the pilots had some moderate to severe-mode confusions or misunderstanding problems. The primary case was the autoflight system making an uncommanded transition into a vertical navigation with altitude hold or an altitude hold mode. This occurred when the pilot delayed in selecting the appropriate descent altitude in the mode control panel altitude window. This procedure is not available in the current 737 and 757/767 aircraft, but is available on the 777 systems. It is clear that not enough attention was paid to this, as well as to other differences during the pilot training and that these problems would have been eliminated if the selection of pilots had been limited only to 777 pilots.

Other problems concerned energy and speed management. Large speed errors were noted in several of the runs. Given that the AMSTAR guidance typically commanded speed changes at 0.5knots/second, the large speed errors, many in excess of 20 knots, occurred over large intervals of time. Several pilots failed to add drag when they needed to decelerate while descending and instead they tried to control the aircraft's energy by changing the vertical navigation modes. Since several of the arrival paths required aggressive energy management to maintain proper speed and altitude, incorrect or inadequate use of the aircraft's grad devices quickly put the pilots into situations from which recovery was difficult. It is worth mentioning that all of the subject pilots allowed, in the first run, to accelerate away from the planned speed at the initiation of the glideslope intercept. That is, if the aircraft were in level flight prior to glideslope intercept, the descent onto the glideslope would require the immediate application of flaps or landing gear to maintain the speed. Any delay in configuration deployment would allow the airplane to accelerate away from the planned speed. An example of such behavior showed significant speed deviations close to the final approach fix. Starting at the deceleration point of 170 knots, the aircraft is slow in decelerating causing a positive speed deviation. At about 100 seconds before the final approach fix, the glideslope was intercepted and the aircraft started to descend but without adequate drag to maintain speed. Between this point and the final approach fix, the aircraft accelerated to 185 knots and the pilot made no changes to the aircraft configuration. The AMSTAR speed was 155 knots and was limited by the aircraft configuration. AMSTAR issued a caution that additional drag was required but this was not acted upon. Just inside the final approach fix the pilot was alerted that the aircraft was approaching the minimum safe distance behind the lead aircraft. This alert is displayed on the navigation display and caused the pilot to react. The pilot was able to slow the aircraft to its final approach speed just before crossing the threshold. In a real-life operation, this would clearly be unacceptable and the controller would have to intervene. It appears that the pilot lost attention to the simulation for the last two minutes before the final approach fix. No obvious cause was identified, but this could be attributed to the fidelity of the simulation or to the fact that this was the last data run for this pilot.

Only one specific AMSTAR situation encountered, when the pilot seemed to be confused by the speed guidance given when the AMSTAR was first engaged. When the spacing clearance was issued, the aircraft already had a negative spacing error and thus commanded a slower speed than what the aircraft was currently flying. The pilot seemed to expect AMSTAR to maintain the current speed and tried twice to reinitialize AMSTAR before accepting the slower speed. This all occurred over about 20 seconds and there were no further problems for this pilot.

The questionnaires ratings analysis focused on the mean ratings for all subjects for a particular question and for all ratings given by each subject for a particular run. The questionnaire were classified into (1) post-scenario questionnaires, where the pilots provided insights into AMSTAR tool and the precision spacing concept and (2) post-experiment questionnaire, where both pilots and controllers were asked questions about the conduct of the experiment as well as training. The post-scenario questions concerned the needed level of attention for each phase of flight, the pilot's frustration level and assessment of their success in meeting the spacing goal and the acceptability and usability of the speed guidance and information presented. There were also to open-ended questions, where the pilots could give additional feedback. All answers had to refer to the scenario just finished. In the post-experiment questionnaire, the pilots were asked to rate the overall usefulness and reliability of the tools and procedures. The controllers were asked about the acceptability of the operations and if they thought these operations could be integrated into today's traffic flow. The controllers were also asked to offer real-world situations or constraints that they thought would affect these operations.

The questions were rated based on a seven-point scale with 7 being the most positive and 1 being the most negative answer. Questions regarding the level of success, frustration and attention were broken down by the phase of flight. The responses were, in general, overwhelmingly positive. For the attention, frustration and success questions, the average responses were above 6.0. The majority of responses to all questions, among all subjects, had ratings of 5 or greater with 7 representing nearly half of all ratings. An example of such post-scenario and post-experiment questionnaire can be found in [37].

The average rating of a particular question among all subjects provided insight into how well the run went. For example, a high rating for a question regarding the level of attention required to follow the spacing procedure would indicate that most subjects found the level of attention required acceptable for that run. For the questions regarding frustration and performance, some pilots gave low responses to the level of frustration perceived (high frustration) and low ratings of their own performance in flying the approach, for the middle and final portions of the approach.

The average rating for a particular subject for a run, would provide insight into the subject's overall success for that run. In general, it was noted that if a subject rated all components of one question unusually low, he also rated all or many components of other questions unusually low as well. For instance, subject that rated the "attention required" as high, also rated frustration as high, evaluation of their own performance as low, and usefulness of AMSTAR guidance and other information sources as low. The experiment was not designed to be an accurate measurement of controller workload nor AMSTAR's effects on it. In a real-world environment, controllers would have other non-equipped aircraft to control, transient aircraft, weather, coordination and many other activities to tend to. Therefore, in the absence of these other tasks and because of the high level of success of the AMSTAR tool in keeping in the arrival flow properly spaced, the controllers actually were left with little else to do. Therefore, many of the controller ratings of the concept, the observations of the experiment airspace and procedures and the progress of the precision spacing aircraft along the arrival route were extremely high. They did however provide very useful insight on questionnaire items where they were asked to provide comments and not rating values.

One question asked the controllers what real-world factors, which were not represented in this simulation, they thought would hinder airborne merging and spacing operations. Responses included resistance to change, dynamic weather (thunderstorm activity and the re-routing it may require, widely variable winds between velocity, direction and altitude) and a re-sequencing go-around and unscheduled arrivals. Other raised concerns included AMSTAR application and procedures associated with arrival routes that have transitions to multiple runways.

Nonetheless, quite positive comments were registered, such as “I believe the overall efficiency of the system can be greatly increased with this equipment and these procedures” or “As an active controller, having worked this, I hate to go back to the old (present) way”.

3. The Causal Model for Air Transport Safety (CATS)

3.1. Introduction

The Causal Model for Air Transport Safety (CATS) has been commissioned by the Dutch Ministry of Transport and is being developed by a consortium including Delft University of Technology, The National Aerospace Laboratory (NLR), Det Norske Veritas (DNV) and White Queen. The project arose from the need for a thorough understanding of the causal factors underlying the risks implied by the air transport, so that efforts to improve safety can be made as effective as possible [4]. The objective is to develop a fully operational causal model that represents the causes of commercial air transport accidents and the safeguards that are in place to prevent them. The purpose of the developed model is to describe the air traffic system and its safety functions in such a way that it is possible to analyze risk reductions alternatives.

As aviation is an extremely complex system, to further limit the size of the developed model, only the primary process of flying from A to B is considered. This primary process is further subdivided into several flight phases: take-off (TO), en-route (ER) and approach and landing (AL). The numerical estimates derived in the model apply to “average”, modern world-wide commercial air transport, which, in terms of aircraft, translates to a “western-built” aircraft, heavier than 5700 kg, maximum take-off weight. The whole system is embedded in international and national regulations.

The proposed risk model architecture includes Event Sequence Diagrams (ESDs), Fault Trees (FTs) and Bayesian Belief Nets (BBNs). The driving idea of causal modeling is that a cause is the occurrence of a particular combination of the values of relevant parameter that gives rise to an effect. ESDs represent the main events that might occur in a typical flight operation and the potential deviations from normal. FTs represent causes for these deviations and are designed to quantify the probability that these deviations occur. BBNs describe human performance models, which are designed to describe the actions of people involved in flight operations and to quantify their probability of error.

The methodology used in CATS differs from the technology used in many risk analysis models, by its use of a single model structure based on the BBNs. FTs and ESDs are therefore combined into an integrated network model, as will be described below.

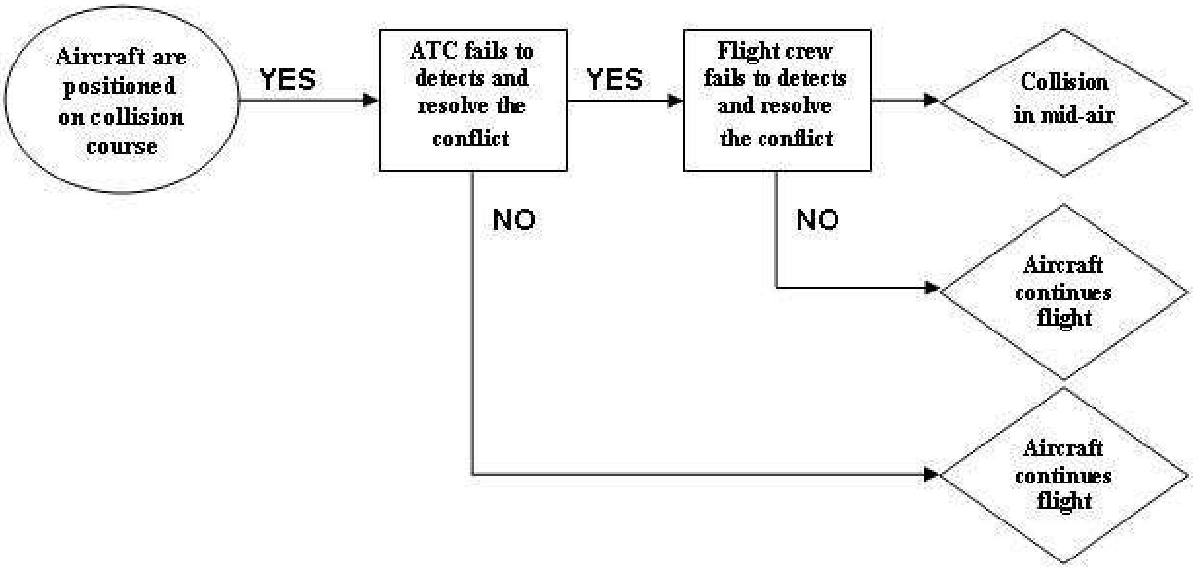
3.2. Event Sequence Diagrams (ESDs)

Aviation accidents result from a combination of many different causal factors (human error, technical failures and management failures), in certain characteristic accident scenarios. The accident scenarios are grouped by the accident type and the flight phase in which they occur. The main accident types considered in the CATS model have been defined based on the ICAO definition of an accident. The Event Sequence Diagram methodology is used in the model to represent the considered accident scenarios.

An Event Sequence Diagram (ESD) is a flow chart with paths leading to different end states [1]. Each path through the flow chart is a scenario. The event sequence starts with an initiating event, such a perturbation that requires some kind of response from operators, pilots or one or more systems. Along each path, pivotal events are identified as either occurring or not occurring. ESDs are used to analyze forward; for each event, the resulting potential following events are identified.

32 such ESDs are currently integrated in the risk model, which cover all possible accidents. The combined ESDs represent all dangers or hazards that each flight has to overcome in order to safely complete the journey. A list which contains the ESDs is provided in Appendix A. The name of each ESD is given by its initiating event. The complete description, the definition of all the events as well as the quantification of the ESDs can be found in [1]. Fig.3.1 illustrates the representation of ESD31 – Aircraft are positioned on collision course.

Figure 3.7 ESD31 – Aircraft are positioned on collision course.



Conventionally, the ellipse is used to graphically represent the initiating events. The pivotal events are represented by rectangles and have two outcomes, typically “yes” and “no”, corresponding to event occurrence and non-occurrence. The rhombus is used to represent the end states of the accident scenarios. However, these delimitations will disappear once all the ESDs will be integrated into the overall network model.

Event Sequence Diagrams are used to analyze forward. This means that for each event, the resulting potential following events are identified. The ESDs provide a qualitative description of the accident scenarios. Intentionally, the events in each ESD are kept broad and generic, in order to cover many similar situations. The detailed specific or possible causes or contributing factors of these events are added, where necessary, through other layers of the model, such as Fault-Trees or Bayesian Belief Nets.

The end states of an ESD also have color coding to indicate that:

- The challenge represented by the ESD did not present itself or is overcome and no residue is left - the GREEN state.
- The challenge was met, but some residual problem remains, which may influence the outcome in some other ESD in the chain - the ORANGE state.
- The challenge could not be met and an accident occurred – the RED state, which typically implies the end of the flight.

Each ESD has been quantified by assessing the probability of occurrence of each of the different pathways. The probability of occurrence of various accident scenarios are expressed as a function of the initiating events. The probability of occurrence, for each flight, of initiating events was determined from occurrence data, i.e. airline's occurrence reporting system. The probability of occurrence, per each flight, of the end states was quantified from accident data. The pivotal events have been quantified using conditional probabilities, computed from the initiating event and end state probabilities. All probabilities have been provided as point estimates [17]. All ESDs have been quantified using alternative sources of data.

The NLR Air Safety Database has been used as a primary source of data. Besides accident and incident data, the Safety Database also contains a large collection of non-accident related data, including airport databases, weather data and fleet data. However, Airclaims and ICAO ADREP were the primary accident data source, for the time period 1990-2003. Moreover, for some ESDs, ASRS and NTSB databases have been used as well. The primary sources of data for the quantification of the probability of occurrence of the initiating events are the Service Difficulty Reports and Air Safety Reports; however, when more accurate, other sources of data were used [1].

Certain assumptions were made with respect to the quantification of the ESDs. These assumptions were necessary in order to restrict the complexity of the model or because of the limitations on available data. Consequently, among others, it was assumed that the data samples which are being used for quantification are representative for the type of air transport at which the risk model is aimed. Moreover, each occurrence in the data samples could be uniquely and unambiguously assigned to a particular ESD. It was assumed that the data bases which are being used in the analysis are complete, i.e. that there were no over reporting, under reporting or any other bias in the data bases. Where no examples or specific accident scenarios were found in the data sample, the probability of occurrence of that scenario was assumed zero. Also, it was assumed that events in the ESD cannot occur partially. Nonetheless, no dependencies between the developed ESDs were assumed.

In CATS, ESDs are combined with Fault-Trees, as it will be shown in the following section.

3.3. Fault-Trees (FTs)

Fault-Trees best represent the logic corresponding to failure of complex systems. CATS uses fault trees to model in sufficient detail the causes of each initiating and pivotal event in each ESD. The FT should show the breakdowns causes of these events, to the extent that this is possible within the limitations of the fault tree modeling. The initiating and the pivotal events in ESD are the top events in the fault trees. While the ESDs show physical events preceding the accident, the FTs are able to show logically necessary events for the accident to occur.

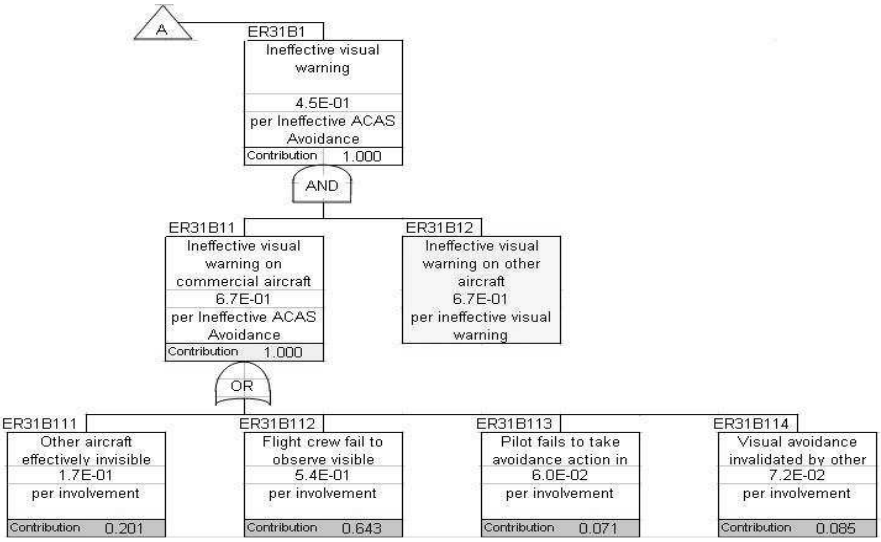
The aim of the FTs is to describe the occurrence of an event in terms of the occurrence of other events or causes. As they are logical trees, the state of each block in the FT can only be true or false. “True” usually means that the process described in the block is in the failed state, whereas false describes the opposite state. A property which can be exploited in the FTs is that the order in which the blocks occur can be chosen independently of the time sequence. Therefore, in CATS the order of events is given by the order of logical causality.

In CATS, the FTs are also used to integrate barrier models, representing defenses against accidents. The FT is constructed such that each AND gate has only two entries:

- A cause and
- The failure of the barrier that is supposed to prevent the cause to propagate towards the accident.

When a FT is quantified, probabilities are attached to each of the blocks, i.e. probability at any given time that the condition in the block is true (the corresponding system is failed). Some of the quantified probabilities are assumed independent (i.e. the probability of the onboard monitoring being ineffective is independent of the probability of the brake system failure). Other probabilities are evaluated under the condition that other blocks in the tree are true, which leads to conditional probabilities. All trees have been modeled such that all the probabilities on the right hand side branches under the AND gates are conditioned on the left hand block being true. For example, in Fig. 3.2, the probability of “Ineffective visual warning on other aircraft” is conditioned on the left event, “Ineffective visual warning on commercial aircraft”. For each event, the tree provides the failure probability per demand. For the events on the extreme left side, the relevant demand is a flight. Also, the contribution of each event to the failure of the corresponding barrier is provided, as shown in the picture below.

Figure 3.8 Part of the FT associated with ESD31



In the FT, the probabilities of events generated by the AND or OR gates are quantified from the probabilities of the two inputs and assuming independence, as follows:

$$P(A \text{ AND } B)=P(A)P(B)$$
$$P(A \text{ OR } B)=1-(1-P(A))(1-P(B)).$$

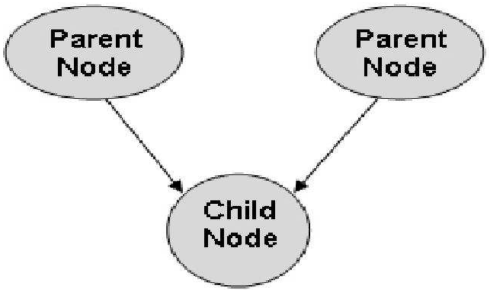
The development of the FT model has followed the same approach as used by the Eurocontrol Integrated Risk Picture. In CATS, the FTs were quantified using a top-down approach, which ensured that the overall probabilities are consistent with the actual accident data. Also, as a method of validation, the FTs were quantified independently of the ESDs, which create an opportunity for comparison. The FTs provide best estimates of the average probabilities of events among commercial flights world-wide. The current state of the fault tree development is documented in detail in the DNV reports.

The base events of the FTs include events representing human reliability. These events will be detailed throughout another layer of the model, which will be described in the following section.

3.4. Bayesian Belief Nets (BBNs)

A Bayesian Belief Net is a Directed Acyclic Graph (DAG), fig. 3.3. BBNs are an appealing graphical tool for specifying high dimensional uncertainty distributions. The nodes represent random variables and the arcs denote dependence statements between adjacent nodes.

Figure 3.9: Example of a simple BBN, where a child node has two parent nodes.



BBN represent a graphical visualization of the knowledge including interactions among various sources of uncertainty. The advantage of the BBN is that it is intuitively easier to understand direct dependencies and local distributions than complete joint distribution. It can be used to answer probabilistic queries - the net can be used to observe changes in the joint distribution when evidence is available. This is called probabilistic inference.

Three different approaches to model BBNs have been proposed in literature: discrete, normal and non-parametric. Each approach will be briefly reviewed, along with its advantages and disadvantages.

3.4.1. Discrete BBNs

A discrete BBN requires the specification of marginal distribution for all source nodes and conditional probability tables for all child nodes. The main attractive feature of discrete BBNs is the fast updating algorithms. On the other hand, they carry a very heavy assessment burden, For example, a BBN model where a child node has 6 parent nodes and all nodes have 5 states, would require specifying 78125 (5^7) conditional probabilities. Moreover, if data is available for the marginal distributions of the child nodes, it is very difficult to construct conditional probability tables which comply with the marginal data. Hence, modeling discrete BBNs requires a drastic discretization of the nodes or a simplification of the model. For these reasons, discrete BBNs are unsuitable. As more flexibility was needed with this respect, a continuous approach seemed appropriate.

3.4.2. Normal BBNs

Continuous BBNs were first developed for joint normal variables. The influence of the parents on a child is interpreted as partial regression coefficients, when the child is regressed on the parents [2]. For each normal variable, the unconditional mean and, by assumption constant, conditional variance must be assessed. For each arc, a conditional regression coefficient must be assessed. Discrete nodes can be also represented using this model, with the restriction that continuous nodes can have discrete parents but not discrete children. The main advantage of the approach is that it enables analytical updating. However, assessing partial regression coefficients may be unintuitive, especially if the variables must first undergo transformation to joint normal.

If the normality assumption does not hold, then the variables must be transformed to normal variables. The conditional variance in normal units must be constant and partial regression coefficients apply to the normal units of the transformed variables, not to the original units, which place heavy burden on any expert elicitation. Also, if a parent node is added or removed after quantification, then the previously assessed partial regression coefficients must be re-assessed. Therefore, if the normality assumption does not hold, which is often the case, all the above requirements make the normal BBNs unappealing for modeling high dimensional probabilistic models.

3.4.3. Non-parametric BBNs

In Kurowicka and Cooke [3], a non-parametric approach has been proposed for the continuous BBNs. Hence, no joint distribution is assumed. In order to quantify BBNs using this approach, one needs to specify all one-dimensional distributions and a number of (conditional) rank correlations equal to the number of the arcs in BBN, which connect the probabilistic nodes.

Each node is assigned with a continuous invertible univariate distribution function. The dependence between variables is described in terms of (conditional) rank correlations, given the advantages over other dependence measures, i.e. the product moment correlation. The (conditional) rank correlations are algebraically independent, hence any number between [-1, 1] can be attached to the arcs of a continuous/discrete non-parametric BBN. However, the rank correlations between the variables are assumed constant. Therefore, a situation where X and Y are positively correlated when variable Z takes low values, but are negatively correlated when Z takes high values cannot be represented.

Therefore, all the required specifications along with a bivariate tool that realizes the correlations and exploit the conditional independence properties implied by the BBN structure uniquely determine the joint distribution. Unlike the previous normal approach, for distribution free continuous BBNs, the updating must be done by Monte Carlo simulations. However, a particular choice of the bivariate tool enables an analytical updating for the continuous/discrete non-parametric BBNs.

Nodes and arcs can be added or deleted from a BBN quantified with this protocol without re-assessing previously added correlations. Moreover, the dependence structure is meaningful for any such quantification and need not be revised if the univariate distributions are changed. However, conditional rank correlations are not elicited or estimated directly from data. They are obtained from (conditional) exceedence probabilities. Suppose that in fig.2.3, the child node is denoted by A and the parent nodes are denoted by B and respectively C. According to the protocol the rank correlation r_{AB} and the conditional rank correlation $r_{AC|B}$ have to be assessed. The correlations are obtained from the answers to the following questions:

- “Suppose that B was observed above its median, what is the probability that A is also above its median?”
- “Suppose that B and C were both observed above their medians, what is the probability that A is also above its median?”

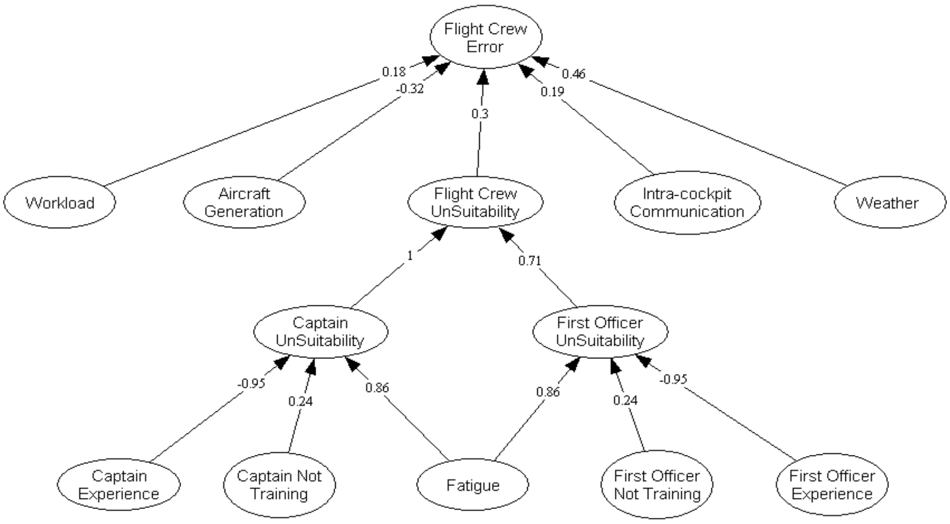
The above discussion concerns only probabilistic nodes; however, a node in a BBN can also be functional, i.e. its values result from functional relationships of other random variables rather than from its assigned distribution. For functional nodes, the functional relationship captures all the influences between the parent nodes and the child node. Hence, there is no need to assess (conditional) rank correlations to the arcs connecting functional nodes. It is noteworthy that the influence defined by the (conditional) rank correlation can be regarded as being "softer" than the influence determined by the functional relationships.

In order to capture the influence of the human operator on accident causation, its role has to be properly represented in the causal model. The human operator is best represented in a BBN, as it involves primarily "soft" influences rather than deterministic cause-effect relations. Therefore, the continuous/discrete non-parametric BBNs were firstly used to realize the human behavior models in CATS:

- Flight Crew performance model;
- Air Traffic Controller (ATCo) performance model;
- Maintenance model.

Fig.3.4 represents the Flight Crew Performance model. The definition of all variables included in the model is provided in Appendix B.

Figure 3.10: BBN representing the Flight Crew Performance model in the CATS model



As previously mentioned, each node (variable) in the human performance model is assigned with a continuous, invertible univariate distribution function. Whenever possible, the marginal distributions have been quantified using available data. Otherwise, the quantification has been assessed using structured expert judgment. In the Flight Crew (FC) performance model, five marginal distributions have been quantified using expert judgment – Captain Unsuitability, First Officer Unsuitability, Crew Unsuitability, Intra-Cockpit Communication and Workload. For these probability distributions, experts' uncertainty estimates for variables of interest are elicited via a structured protocol of questions. The elicitation also includes variables whose true values are known, called calibration variables. These variables are used to measure and validate the expert performance in uncertainty quantifications. For each question, three numbers will be required, the median, the 5% and the 95% percentile value.

The elicitation question for the Captain Unsuitability variable was formulated in the following manner:

"Consider 10,000 Captains chosen at random from the total population. Suppose the same proficiency check test is performed today on these 10,000 randomly chosen Captains. How many of them will fail the proficiency test?" (Q1)

The population herewith considered referred to western-build aircraft currently flying in commercial operations worldwide. Similar questions have been asked for quantifying the probability distribution of the other four variables. The marginal distribution for the Flight Crew Error followed from each associated FT, as further detailed. The associated event in the fault tree was used to estimate the basic human error probability.

In addition, the information on the relation and dependencies between the variables in the Flight Crew performance model has also been assessed using expert judgment protocol. As previously stated, conditional or unconditional rank correlation has been elicited using probabilities of exceedence and using the estimates from the marginal distribution elicitation, as further described:

"Suppose that instead of selecting 10,000 Captains at random in Q1 you select 20,000 Captains at random. Suppose that out of the 20,000 you select 10,000 for which Experience is at least equal to its median value. What is your probability that in this (not randomly chosen) pool, the median value of Captains that fail the proficiency test will be more than your median estimate provided in Q1?"

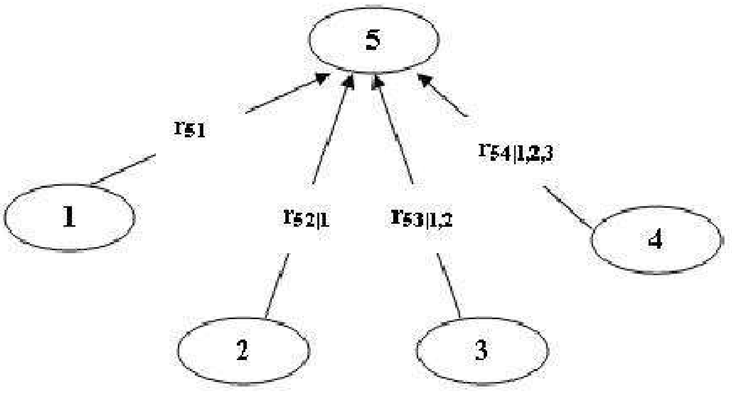
"Suppose that instead of selecting 10,000 Captains at random in Q1, you select 40,000 Captains at random. Suppose that out of the 40,000 you select 20,000 for which Experience is at least equal to its median value and from these 20,000 you select 10,000 for which Fatigue is also at least equal to its median value. What is your probability that in this (not randomly chosen) pool, the median value of Captains that fail the proficiency check test will be more than your median estimate provided in Q1?"

"Suppose that instead of selecting 10,000 Captains at random in question Q1, you select 80,000 Captains at random. Suppose that out of the 80,000 you select 40,000 for which experience is at least as equal to its median value. From these 40,000 you select 20,000 for which Fatigue is also at least or equal to its median value and finally out of these 20,000 you select 10,000 for which Training is also at least equal to its median. What is your probability that in this (not randomly chosen) pool, the median value of Captains that fail the proficiency check test will be more than your median estimate provided in Q1?"

Obviously, the above elicited conditional probabilities are not independent, and the answer to one question constraints the answers to the following questions. An elicitation software support tool called UniExp has been developed to facilitate the visualization of these constraints. In the same time, the expert acquires an intuitive grasp of the meaning of influence between nodes. The first question can informally translate to “What is the probability that Captain Unsuitability is above median, given that Captain Experience is above median?” and the answer to this question is employed to compute the unconditional rank correlation between Captain Unsuitability and Captain Experience. The same protocol applies for the following two questions. Consequently, the conditional rank correlation between Captain Unsuitability and Captain Training, given Captain Experience and Fatigue will follow from the answer to the last question.

Other approaches have been proposed to elicit conditional rank correlations. The protocol used for the Air Traffic Controller performance model implied eliciting ratios of rank correlations. Once the first conditional probability has been assessed and translated to its corresponding rank correlation, the analyst may elicit ratios of rank correlations and translate them into conditional rank correlations. In the example below, the first (unconditional) rank correlation, r_{51}, will follow from eliciting the corresponding probability of exceedence. Afterwards, the ratio $\frac{r_{51}}{r_{52}}$ will be elicited and translated into the (conditional) rank correlation $r_{52|1}$, followed by the elicitation of $\frac{r_{51}}{r_{53}}$, which will translate into $r_{53|1,2}$ and so on.

Figure 3.11: Example of BBN with 5 nodes. The dependence relationships are specified using (conditional) rank correlations.



As in the previous approach, the answer to each of the subsequent questions is constrained by the answers provided at previous questions. Hence, at each step of the elicitation, bounds for the rank correlation ratios have to be computed. The experts’ new assessments will depend on these bounds derived from his previous answers.

This approach has been used to quantify the dependence structure for both the Air Traffic Controller and Maintenance performance models and will also be employed to assess the new dependence relationship considered during this research. Even though this protocol relies on an arguably unintuitive rank correlation ratio elicitation, it overcomes an important limitation of the first elicitation method. Namely, the first method major drawback is that the number of parent nodes for a child node must be limited to 5 or 6 maximum. Reliable estimation of the combined influence of more than 5 or 6 influences is considered to be impossible.

The human reliability models account for the probabilistic relationships of the model. Whenever a base event in a FT represents a flight crew failure, it should be linked to the flight crew performance BBN. The same procedure applies for base events corresponding to an ATCo failure or from a maintenance failure. All values of the human performance variables are expressed in objectively quantifiable unit. The role of the BBNs in the integrated network model will be revealed in the following section.

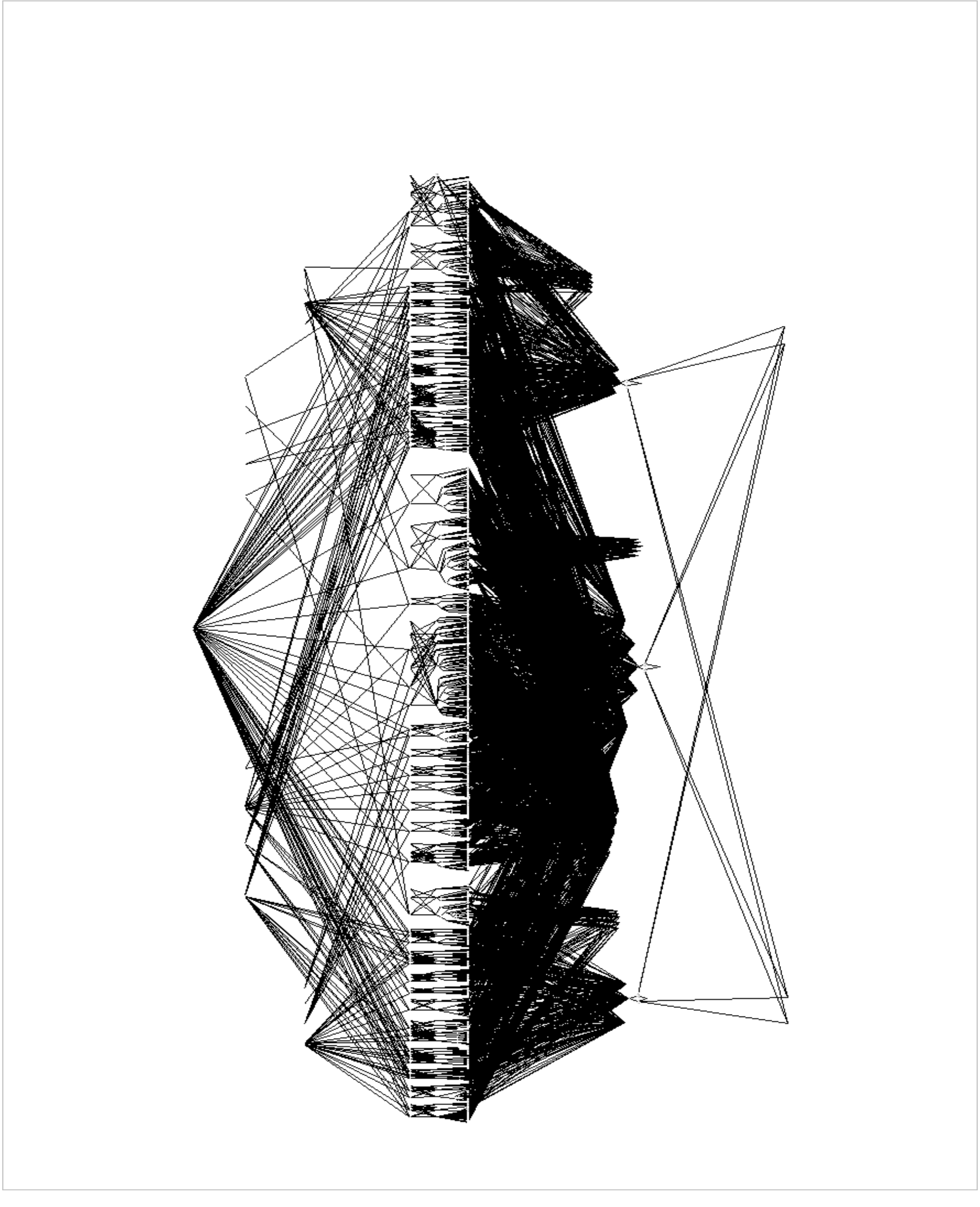
3.5. The Overall Network Model

As illustrated in the previous section, the sequences of events that may lead from cause to consequence could also be represented as a series of nodes connected with arrows. The nodes represent events and the arcs the relations between these events. As previously mentioned, there are relations that can be represented by functional dependencies. The Boolean functions enable ESDs and FTs to be fully represented as functional nodes in a BBN. Furthermore, it is noticeable that both FTs and ESDs have the essential properties of a directed acyclic graph. If all the elements of the model are treated as directed acyclic graphs, they can be combined into one integrated model. The method developed for CATS translates a fault tree into the equivalent BBN. In this particular BBN, any node can only take two values and the state of the upstream nodes is completely determined by Boolean combinations of the downstream nodes. By translating in this way a FT into a BBN, they will become a part of a larger BBN, which will allow the quantification in a single operation. The same procedure can apply to translating an ESD into a BBN. The ESDs form the basis to build the backbone of the model.

The integrated BBN has been implemented using Uninet, a software application developed at The Department of Applied Mathematics, Delft University of Technology. Uninet has been developed to efficiently implement large scale continuous/discrete non-parametric BBNs modeled in the CATS model. The software is able to provide analytical updating for large scale sized models in reasonable time. Model learning may also be performed in Uninet, though this feature will not be exploited here.

In CATS, for the upper layers, the unconditional distributions are computed from the Boolean functions previously described. The expectation of each distribution is regarded as the probability of each event. The distribution in each functional node represents the uncertainty propagated through each sample of the base events in the FT. Therefore, by assigning the corresponding distributions to the base events, by applying formulas to the functional nodes implied by the existing Boolean functions and by sampling the distributions of these functional nodes, the obtained mean of this distribution will be equal to the conditional probabilities computed form the occurrence data. The most recent representation of the integrated BBN is illustrated below.

Figure 3.12: CATS overall network model



The model consists of 1365 nodes at the moment. From these, 532 are functional nodes, representing ESDs and FTs as Boolean functions and 833 are probabilistic. The probabilistic nodes are different instances of the human performance models and other base events in the FTs. Since the marginal distributions of the human errors are different for each accident scenario in each flight phase, each corresponding error has to be quantified separately. Nevertheless, in the continuous-discrete non-parametric BBN approach used for the model, the dependence information for each human performance model remains equal across different instances of each model. Hence the quantification of dependence needs to be done only once. Performing initial sampling of the unconditioned model net takes approximately 4 minutes. Sampling the conditioned net takes approximately 150 seconds.

An obvious remark with respect to the picture above is that the more the model resembles reality, the less intuitive it is. However, the integrated BBN was structured in layers which correspond to the constituent elements. The bottom layer of the integrated model represents the human performance models. Both Flight Crew and ATCo performance models are included for each flight phase. The Maintenance model is obviously included for the whole flight. The upper layer corresponds to the ESDs and their corresponding FTs. The main outcome of the model is the accident probability per flight. Moreover, the probabilities for different accident categories are also available, such as collision with ground, collision in mid-air, control flight into terrain (CFIT), runway veer off and others.

4. A Merging and Spacing (M&S) Approach to the CATS model

4.1. Assumptions

The M&S concept of operations is designed to accommodate both AMSTAR equipped and unequipped aircraft in the merging arrival stream. For operational viability, unequipped aircraft can also participate in this concept of operation, by following the charted arrival routes. By broadcasting its data, the unequipped aircraft can serve as the leading aircraft for an equipped aircraft. Hence, ADS-B is a required capability for every aircraft in the system, in order to achieve the desired capacity goal in a safer environment. ADS-B could also provide warnings of high terrain and obstacles, updated weather reports and advanced warning of weather status as well as warnings for avoiding other aircraft. However, for the initial implementation of merging and spacing operations, it will be assumed that ADS-B reports will only contain state data and intent information (route and final approach speed) of the leading aircraft.

The airborne technologies that interact with the AMSTAR tool are auto throttle, speed display and area navigation (RNAV) system. Merging and Spacing is accomplished using RNAV routes, hence the aircraft will be equipped with the capability to compute and fly RNAV routes. In this concept, incoming aircraft are assigned RNAV routes from terminal area entry to ILS intercept. The RNAV routes include a lateral path and a nominal vertical and speed profile. The route is used as a reference trajectory by the spacing tool. All altitude crossing restrictions are based on published data for the route and were used to select the appropriate descent altitudes.

No design errors will be assumed for the risk assessment, i.e. the system works as it is intended to work. Moreover, it will be assumed that the flight crew has sufficient training with respect to the concept of operations and the procedures implied by AMSTAR. Nonetheless, as the current stage of development focuses only on airborne technologies and procedures, no enhanced ATCo capabilities will be considered. However, it will be assumed that the ATCo spacing clearances imply wake vortex-based minimum separation criteria.

The following risk benefits have been identified:

- Reduced air/ground communication, therefore reduced probability of lost or garbled communication;
- Reduced radio congestions;
- Increased flight crew situation awareness, due to the onboard automation;
- Reduced flight crew error, due to the new onboard automation;
- Reduced ATCo error, due to reduced radio traffic;
- Mitigation of errors based on a redistribution of workload between pilots and controllers;
- Risk benefits implied by the use of ADS-B.

The considered risk penalties are the ones implied by the increased traffic volume the concept addresses. This will result in a possible increased separation infringement, due to reduced spacing intervals between aircraft. However, it should be borne in mind that these can be compensated by the increased ATCo avoidance capabilities. Dynamic weather and unscheduled arrivals might also contribute to increased separation infringement.

Mid-air collisions, reduced safety margins, loss of control in flight and collision with ground (CFIT) have been regarded as possible hazards for the merging arrival stream aircraft. These accident categories will be further considered for numerical estimates.

In the following sections, CATS will be employed to assess the aforementioned risk benefits and risk penalties implied by the M&S concept. In order to achieve these assessments, possible influences of the concept on the model have to be considered first.

4.2. Changes in ESDs and FTs

A top-down approach has been considered for identifying the M&S influences in CATS. This was achieved by considering possible influences in the most generic layer of the integrated network, the ESDs. It has been decided to maintain the existing topology of the ESDs, as by definitions these cover all accident scenarios. Therefore, proposing a new ESD would actually involve re-defining the existing ones.

The ESDs describe accident scenarios for each accident category in each flight phase. As the M&S concept aims to improve terminal area operations, only the ESDs that cover the en-route (ER) and approach and landing (AL) accident scenarios have been considered:

1. ESD11 – Fire on board
2. ESD12 – Flight crew spatially disoriented
3. ESD13 – Flight control system failure
4. ESD14 – Flight crew incapacitation
5. ESD15 – Anti-ice/de-ice system not operating
6. ESD16 – Flight instrument failure
7. ESD17 – Aircraft encounters adverse weather
8. ESD18 – Single engine failure
9. ESD19 – Unstable approach
10. ESD21 – Aircraft weight and balance outside limits during approach
11. ESD23 – Aircraft encounters windshear during approach
12. ESD25 – Aircraft handling by flight crew during flare inappropriate
13. ESD26 – Aircraft handling by flight crew during landing roll inappropriate
14. ESD27 – Aircraft directional control related system failure during landing
15. ESD28 – Single engine failure during landing
16. ESD29 – Thrust reverse failure
17. ESD30 – Aircraft encounters unexpected wind
18. ESD31 – Aircraft are positioned on collision course
19. ESD33 – Cracks in aircraft pressure cabin
20. ESD35 – Flight crew decision error/operation of equipment error (CFIT).

The definitions of the initiating events which define the ESDs are included in Appendix D.

From the above listed 20 ESDs, some of the ESDs describe sequences of events that would not change due to M&S, i.e. ESD11, ESD21, etc. Others seemed to be possibly influenced, but after thorough review of the events definitions, the situation described was not applicable for any change. For example, flight crew spatially disoriented refers to disorientation with respect to the attitude (pitch, roll, and yaw) of the aircraft only. Disorientation with respect to aircraft's position and altitude are excluded.

Therefore, only 6 ESDs were relevant for studying possible influences of the M&S concept:

1. ESD17 – Aircraft encounters adverse weather
2. ESD19 – Unstable approach
3. ESD23 – Aircraft encounters windshear during approach
4. ESD30 – Aircraft encounters unexpected wind
5. ESD31 – Aircraft are positioned on collision course
6. ESD35 – Flight crew decision error/operation of equipment error (CFIT)

Not all the base events in the above ESDs will be affected by the concept. For example, one would not expect the probability of severe turbulence, per landing (ESD19). Hence, for each of these ESDs, the corresponding affected base events of the subsequent FTs have been identified and considered for changes. The base events have been grouped in weather related failures and communication failures, ATCo and flight crew errors with respect to improper communication, failures to maintain speed. The list of the influenced base events can be found in Appendix G. Moreover, the end events of these ESDs, which might result in an accident, are listed below.

Table 4.1: End events of the affected ESDs, which might result in an accident.

Code	End Event
ER17d1_02	Collision with ground
AL19d1_01	Collision with ground
AL19f1_02	Runway overrun
AL19h1_04	Runway veer off
AL19h2_05	Aircraft continues landing roll damaged
AL19e5_08	Collision with ground
AL19f4_09	Aircraft lands off runway
AL23f1_01	Runway veer off
AL23f2_02	Aircraft continues landing roll damaged
AL23f3_04	Runway overrun
AL30c1_01	Runway veer off
AL30d1_02	Runway overrun
ER31d1_01	Collision in mid-air
AL35e1_01	Collision with ground(CFIT)
AL35f1_02	Collision with ground(CFIT)

The code of these events is the code used in the integrated network model. The definitions, generic probabilities and units, as well as the source data used in quantifications are provided in the "DNV Collected Fault Trees" document. The definitions of these events can be found in Appendix E. It should be mentioned that each end event refers to the specific previous events described by the ESD, as reflected in its definition. For example, "Collision with ground" (ER17d1_02) is defined as "After encounter with adverse weather, flight crew fails to maintain control of the aircraft and it collides with the ground".

To assess how important these parameters are for the main outcome, i.e. the overall accident probability, sensitivity analysis has been performed. It is noteworthy that an important parameter is a parameter for which the reduction of its uncertainty reduces most the uncertainty of the outcome.

Table 4.2: Probabilistic sensitivity methods for the end events in the influenced ESDs.

Predicted variable	Base variable	Product moment correlation	Rank correlation	Correlation ratio
OUT_TOERALAccident	AL19d1_01	0.9686	0.5033	0.9434
OUT_TOERALAccident	AL19h1_04	0.7549	0.4963	0.6086
OUT_TOERALAccident	AL19f1_02	0.6843	0.4929	0.4757
OUT_TOERALAccident	AL19h2_05	0.5804	0.4949	0.3558
OUT_TOERALAccident	AL35f1_02	0.3056	0.4013	0.105
OUT_TOERALAccident	AL19f4_09	0.2217	0.4553	0.0603
OUT_TOERALAccident	ER31d1_01	0.1157	0.3101	0.0134
OUT_TOERALAccident	AL19e5_08	0.0725	0.373	0.0111
OUT_TOERALAccident	AL30c1_01	0.0741	0.1153	0.0082
OUT_TOERALAccident	AL30d1_02	0.0506	0.1492	0.0073
OUT_TOERALAccident	AL35e1_01	0.0722	0.1355	0.0052
OUT_TOERALAccident	ER17d1_02	0.0527	0.2035	0.0028
OUT_TOERALAccident	AL23f2_02	0.0104	0.0562	0.0001
OUT_TOERALAccident	AL23f1_01	0.0093	0.056	0.0001
OUT_TOERALAccident	AL23f3_04	0.0009	0.0186	0

Therefore the predicted variable is the generic accident, denoted here as "OUT_TOERALAccident". The notation represents the code of this node in the model, suggesting that it is an outcome variable and that it represents accidents from all the flight phases (TO, ER and AL).

The sensitivity analysis was performed in Unisens, a software package developed at Delft University of Technology. Unisens can calculate various statistics and sensitivity measures. As dependency measures, only the product moment correlation, the rank correlation and the correlation ratio have been chosen from the 8 probabilistic sensitivity methods available in Unisens.

As noticed in Table 4.2, a decreasing order with respect to the correlation ratio has been chosen, as it is the most general considered dependency measure. Collision with ground as a result of an unstable approach (AL19d1_01) is the most important parameter among the end events of the influenced ESDs. For this base variable, all considered dependency measures are the highest. Moreover, the highest 4 dependencies are represented by unstable approach end events (ESD19). Collision with ground as a result of crew failure (for the definition of end nodes, see Appendix E) is the most important parameter after the unstable approach end events. To gain insight of how influential these end events are among all 64 end events that contribute to the overall accident probability, sensitivity analysis has been performed for all end events that might result in an accident. All the aforementioned dependency measures are provided in Appendix F. Table 4.3 provides only the first 30 most important parameters.

Table 4.3: Probabilistic sensitivity methods for the first 30 most important end events

Predicted variable	Base variable	Product moment correlation	Rank correlation	Correlation ratio
OUT_TOERALAccident	AL19d1_01	0.9686	0.5033	0.9434
OUT_TOERALAccident	AL19h1_04	0.7549	0.4963	0.6086
OUT_TOERALAccident	AL19f1_02	0.6843	0.4929	0.4757
OUT_TOERALAccident	AL19h2_05	0.5804	0.4949	0.3558
OUT_TOERALAccident	AL25d2_02	0.4345	0.4269	0.2157
OUT_TOERALAccident	AL26c1_01	0.3071	0.3379	0.1524
OUT_TOERALAccident	AL35f1_02	0.3056	0.4013	0.105
OUT_TOERALAccident	AL32d1_01	0.2914	0.3748	0.0868
OUT_TOERALAccident	ER18e5_07	0.2713	0.3633	0.0747
OUT_TOERALAccident	AL19f4_09	0.2217	0.4553	0.0603
OUT_TOERALAccident	ER14c1_01	0.1967	0.3735	0.0486
OUT_TOERALAccident	AL25f1_03	0.1389	0.4149	0.0254
OUT_TOERALAccident	ER16c1_01	0.1585	0.4174	0.0251
OUT_TOERALAccident	ER15e1_01	0.1481	0.3729	0.0235
OUT_TOERALAccident	ER18e1_02	0.0806	0.3563	0.0234
OUT_TOERALAccident	AL25d1_01	0.1523	0.4138	0.0232
OUT_TOERALAccident	AL26d1_02	0.113	0.3226	0.0215
OUT_TOERALAccident	ER21c1_01	0.1423	0.405	0.0203
OUT_TOERALAccident	ER31d1_01	0.1157	0.3101	0.0134
OUT_TOERALAccident	AL19e5_08	0.0725	0.373	0.0111
OUT_TOERALAccident	AL30c1_01	0.0741	0.1153	0.0082
OUT_TOERALAccident	AL30d1_02	0.0506	0.1492	0.0073
OUT_TOERALAccident	TO05e1_01	0.0794	0.3716	0.0063
OUT_TOERALAccident	AL35e1_01	0.0722	0.1355	0.0052
OUT_TOERALAccident	ER17d1_02	0.0527	0.2035	0.0028
OUT_TOERALAccident	AL27c1_01	0.0439	0.2874	0.0026
OUT_TOERALAccident	ER12c1_01	0.0505	0.3741	0.0025
OUT_TOERALAccident	TO03d4_05	0.0343	0.1971	0.002
OUT_TOERALAccident	TO02d1_01	0.0443	0.0849	0.002
OUT_TOERALAccident	TO10d1_01	0.0352	0.3374	0.0012

The end events of the influenced ESDs are highlighted. It is noteworthy that the first four most influential end events of the outcome are the end events of the 6 affected ESDs. Moreover, 12 of the considered end events are among the first 26 of all the influential end events.

4.3. Changes in BBNs

According to [20], the “human” factor is a contributing factor for 56% of the fatal accidents in commercial aviation. Hence the need for a risk model which appropriately describes the human factor and its significance in the causal chain of events leading to a fatal accident. As described in the previous chapter, CATS integrates the human factor through three human performance models for the flight crew, air traffic control and maintenance. Each of them incorporates the contributing factors of the corresponding human errors (Appendix B). Both flight crew and ATCo performance models have been reviewed and possible changes with respect to M&S have been considered.

Aircraft situation data are acquired primarily through radar systems, although GPS and ADS-B applications are currently under control by NASA and FAA. In the U.S. system, at higher altitudes, over 90% of the airspace is covered by radar and often by multiple radar systems [22]. The radar processing system is currently the fundamental enabling technology for aircraft surveillance. All the en-route centers and the TRACONS are fed by primary radar. Primary radar relies on reflection technology that provides sufficient data to calculate the range and bearing, but not the altitude of a detected object.

In CATS, the support surveillance technologies are considered in the Man-Machine Interface variable, included in the ATCo performance model (Appendix B). Man-Machine Interface is a 4 state discrete variable, where the first state denotes that the controller uses the radio only, whereas the last state implies that the ATCo uses radio, primary and secondary radar, as well as additional tools (SMGCS, STCA, etc). Given the radar coverage status of the U.S. airspace and the operational procedures implied by the M&S concept, the first state of the Man-Machine Interface variable has not been considered for any risk assessment.

Furthermore, in CATS, an influencing factor of flight crew performance is the aircraft generation. Aircraft Generation is a discrete, four state variable, where first state represents the first generation and the last state denotes the most recent aircraft generation, as described in Appendix B. As previously stated, the M&S concept implies that the aircraft are equipped with RNAV navigation technology. In United States, RNAV was developed in the 1960s and RNAV routes were published in the 1970s. Therefore, the risk quantification approach regarded only the aircraft typically designed starting with the 1980s, which refers to aircraft generation 3 and 4.

As previously stated, reduced air/ground communication represents an important risk benefit implied by the new concept. As it results in reduced flight crew and ATCo errors, communication has to be considered as an influencing factor in the two human performance models. The changes with respect to communication, as well as several general facts about crew/ATCo communication and communication errors, will be detailed in the following section.

4.4. Communication

Radio communication is currently the primary mean of communication between pilots and ATCo. Flight crew and air traffic controllers communicate by radio using VHF (very high frequency) frequencies between 118MHz and 136 MHz (civilian) and VHF 225-400 MHz (military). Usually, a transmission between the controller and the pilot consists of several instructions which specify the aircraft identification, its position and heading (both lateral and vertical), altitude, weather and speed, frequency changes and others. Each transmission should be followed by a readback/hearback protocol in which the pilot reads back the issued clearances and the controller verifies the correctitude of the received instructions.

Usually, an ATC clearance in the terminal area includes instructions for

- Position and heading
- Altitude
- Speed
- Frequency changes
- Others.

A time analysis of ATC radio traffic in a simulated free flight scenario performed by the Royal Institute of Technology, Stockholm [13] recorded a total of 22 hours of radio traffic. Analyzing the total transmission time, the study revealed that over 35% of radio traffic consists of address information, 16% for altitude, 14% for heading/speed instructions, 8% for position and 7% for frequency. The rest accounted for request, courtesy, hesitation, acknowledgement and others. Moreover, an FAA study [11] of approach communications from the five busiest TRACON facilities in U.S. showed that, for the approach control, the most frequently transmitted instructions are headings (22%), speeds (21%) and altitudes (16%).

As described in the second chapter, the M&S concept is initiated by an ATCo spacing clearance, which assigns the aircraft trajectory, the leading aircraft and the required spacing interval. Afterwards, the crew will follow speed cues from AMSTAR; hence no speed instructions will be provided by the ATCo. Moreover, as the aircraft is assumed to have enhanced area navigation capabilities (RNAV), no altitude instructions will be required.

An Eurocontrol study for the parallel concept Sequencing and Merging [10] showed a significant reduction in the number of commands issued. A drastic reduction (36%-53%) of the number of maneuvering instructions (heading, speed, altitude) has been observed. Moreover, for a RNAV-equipped aircraft, heading and altitude clearances would not be needed. As illustrated in [12], the number of controller transmissions is reduced from approximately eight one way transmissions to two or three. The same holds for the pilots. In addition, there are also fewer altitude and crossing restrictions and required speed assignments instructions.

However, the reduction in the number of instructions does not necessarily imply a corresponding reduction in the number of transmissions. Usually an air/ground transmission consists of more instructions; an average number of instructions in a clearance of 4.32 was reported in [10]. However, the duration of a transmission is expected to lessen considerably due to the new operational concept. Therefore, the transmission load was considered instead of the number of transmissions. The communication load can be quantified as either Kbits/hr (number of Kbits that are conveyed or processed per unit of time) or sec/hr. Because it is an influencing factor to the human error and given the available data, it has been decided to consider sec/hr units. Thus the total transmission time between the air traffic controller and the pilot seemed the most appropriate choice for modeling the influences of the M&S concept.

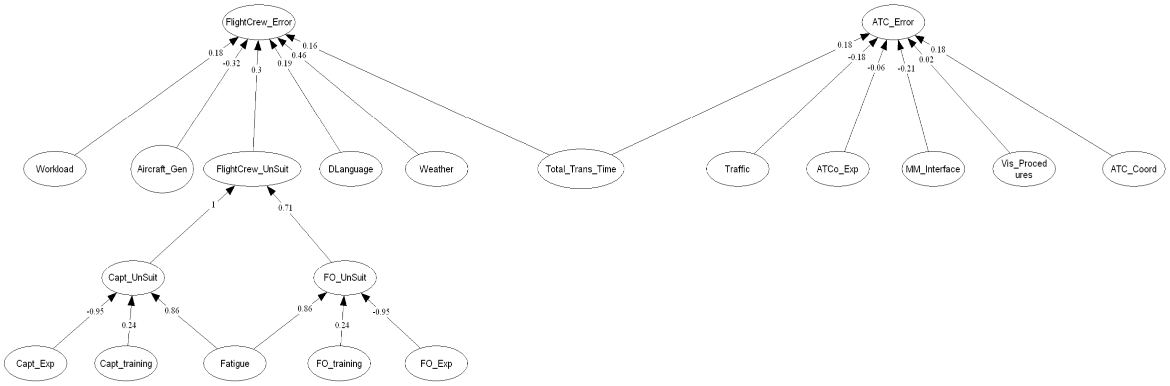
Consequently, as the radio traffic has been identified as one of the concept's benefits, it has been decided to quantify the impact of communication on both flight crew and controller error. Therefore a new variable was added to the model, the Total Transmission Time, which connects the two human performance models, the flight crew performance model and the ATCo performance model. As the M&S operations commence during ER and continue throughout the approach flight phase, the variable has been defined as the total duration, in seconds, of the air/ground communications, per aircraft in the terminal area approach control (TRACON) environment.

The marginal distribution has been quantified using FAA as the data source [11]. The data is based on 50 hours of pilot and controller messages that were transmitted from 5 of the busiest terminal radar approach control (TRANCON) facilities in U.S. between October 2003 and February 2004. Besides the detailed description of routine ATC communication, the report contains pilot readback performance, miscommunications and the effects of ATC message complexity and message length on pilot readback performance. A distribution has been fitted to the data and Gamma seemed to be the most appropriate choice. The parameters and a plot of the fitted data against chosen distribution are provided in Appendix H.

The aircrew/controller communication influences both the flight crew error and the controller error. Hence, the conditional rank correlations the new added variable and the two human errors have to be assessed. Due to time constraints, the rank correlations have been elicited using one NLR expert. The elicitation document can be found in Appendix I. Correlations ratios have been elicited as described in chapter 3. As previously stressed out, the added variable and correlations do not entail a new evaluation of the prior assessed correlations.

Figure 4.13 illustrates the two human performance model linked by the new added variable.

Figure 4.13: Flight Crew performance model and ATCo performance model connected with the new added variable, Total Transmission Time.



The new added variable was linked to every flight crew or ATCo error in the base events from the ESDs corresponding to ER and AL flight phase. Even though only one node has been added to the overall Bayesian network model, 232 arcs had to be connected to human errors. From these 232 human errors in the ER and AL flight phases, only 44 represent ATCo errors; the rest were accounted by the aircrew errors. This high discrepancy between the number of flight crew errors and ATCo errors will be depicted as well in the sequel.

Table 4.4 depicts the sensitivity analysis results for all the contributing factors to the three human performance models. As in the previous analysis, the predicted variable is the overall accident probability. The code of each base variable illustrates the human performance model the contributing factor belongs to and the flight phase for which the variable is defined and quantified. When the factor influences two human errors, both human performance models' codes are used. zFCMNT_TOERALAirGen suggests that the variable Aircraft Generation is influencing both the flight crew (FC) error and the maintenance (MNT) error. Moreover, it influences corresponding human errors in all the flight phases (TOERAL). In addition, the variable is identical for all flight phases.

As highlighted in the table below, the new added variable (zFCATC_ERALTotTransTime) is among the most important human influencing factors. The analysis shows that the reduction of uncertainty for weather in approach and landing reduces the most uncertainty in the overall accident probability. Essentially, 13 most important parameters represent influencing factors for the flight crew error. This can be explained by the high number of flight crew errors compared to ATC and maintenance errors. Hence the new added variable appears to be more important than all influencing factors corresponding to the other two human performance models. Furthermore, total air/ground transmission time is more important than fatigue, First Officer experience or workload.

Table 4.4: Probabilistic sensitivity methods for the contributing factors in the human performance models

Predicted variable	Base variable	Product moment correlation	Rank correlation	Correlation ratio
OUT_TOERALAccident	zFC_ALWeather	0.1369	0.176	0.0388
OUT_TOERALAccident	zFC_ALUnSuitCrew	0.1284	0.307	0.0178
OUT_TOERALAccident	zFC_ERUnSuitCrew	0.1255	0.2901	0.0167
OUT_TOERALAccident	zFC_TOUnSuitCrew	0.1208	0.3018	0.0152
OUT_TOERALAccident	zFCMNT_TOERALAirGen	-0.1048	-0.2404	0.0136
OUT_TOERALAccident	zFC_ALUnSuitFO	0.0956	0.2299	0.0094
OUT_TOERALAccident	zFCTOERALLangDif	0.0771	0.1498	0.009
OUT_TOERALAccident	zFC_ERUnSuitFO	0.0909	0.2137	0.0086
OUT_TOERALAccident	zFC_ALUnSuitCap	0.0824	0.2221	0.0083
OUT_TOERALAccident	zFC_ERUnSuitCap	0.0864	0.2151	0.0078
OUT_TOERALAccident	zFC_ERWeather	0.0694	0.1206	0.0071
OUT_TOERALAccident	zFC_TOUnSuitCap	0.0805	0.2159	0.0069
OUT_TOERALAccident	zFC_TOUnSuitFO	0.0809	0.2202	0.0069
OUT_TOERALAccident	zFCATC_ERALTotTransTime	0.0564	0.0991	0.0057
OUT_TOERALAccident	zFC_ALFatigue	0.0515	0.0803	0.0042
OUT_TOERALAccident	zFC_TOERALExpFO	-0.0688	-0.2145	0.0028
OUT_TOERALAccident	zFC_TOWeather	0.0367	0.1368	0.0026
OUT_TOERALAccident	zFC_TOERALExpCap	-0.0591	-0.2121	0.0018
OUT_TOERALAccident	zMNT_TOERALExpMaint	-0.0297	-0.2198	0.0013
OUT_TOERALAccident	zFC_ALWorkload	0.0298	0.0771	0.001
OUT_TOERALAccident	zFC_ERFatigue	0.0239	0.0331	0.0009
OUT_TOERALAccident	zMNT_TOERALFatigue	0.0273	0.1916	0.0008
OUT_TOERALAccident	zFC_ERWorkload	0.0068	0.0443	0.0004
OUT_TOERALAccident	zATC_ALInterface	-0.0049	0.0176	0.0003
OUT_TOERALAccident	zMNT_TOERALWorkload	0.0161	0.1124	0.0003
OUT_TOERALAccident	zMNT_TOERALCoord	-0.0005	-0.0462	0.0002
OUT_TOERALAccident	zATC_ERExpATCO	-0.0133	-0.0127	0.0002
OUT_TOERALAccident	zATC_ALExpATCO	-0.0038	0.0083	0.0002
OUT_TOERALAccident	zFC_TOERALTrainFO	0.0104	0.0251	0.0002
OUT_TOERALAccident	zATC_TOInterface	0.0085	-0.014	0.0001
OUT_TOERALAccident	zFC_TOWorkload	0.0033	0.0488	0.0001
OUT_TOERALAccident	zATC_TOVisProc	-0.0005	0.0161	0.0001
OUT_TOERALAccident	zATC_TOTraffic	-0.0065	-0.0056	0.0001
OUT_TOERALAccident	zATC_ALTraffic	-0.0074	0.0087	0.0001
OUT_TOERALAccident	zFC_TOFatigue	0.0087	0.0403	0.0001
OUT_TOERALAccident	zATC_TOExpATCO	-0.0001	-0.0065	0.0001

Predicted variable	Base variable	Product moment correlation	Rank correlation	Correlation ratio
OUT_TOERALAccident	zFC_TOERALTrainCap	-0.0019	0.0106	0.0001
OUT_TOERALAccident	zATC_ERVisProc	0.0033	-0.0053	0.0001
OUT_TOERALAccident	zMNT_TOERALWorkCond	0.0078	-0.0072	0.0001
OUT_TOERALAccident	zATC_ERTraffic	-0.0013	0.0147	0
OUT_TOERALAccident	zATC_ALVisProc	-0.0004	-0.0202	0
OUT_TOERALAccident	zATC_ALCoord	0.0021	0.0096	0
OUT_TOERALAccident	zATC_TOCoord	-0.0059	0.0186	0
OUT_TOERALAccident	zATC_ERCoord	0	0.013	0
OUT_TOERALAccident	zATC_ERInterface	0.0038	-0.0336	0

Numerous publications [9][11][15]-[18] have studied the causal factors and possible consequences of radio communication errors. Even though the air/ground communication problem occurrence rate is estimated at 1.4 per 10,000 flights [9], this low rate, however, does not imply a low risk. Voice communication problems can result in potentially high associated hazards. For instance, miscommunication has been identified as a primary factor causing runway incursions (Eurocontrol, 2003). Also, communication problems have been identified as a factor in over 70 percent of operational errors and pilot deviations (Danaher,1993).

Furthermore, a human-in-the-loop experiment performed by FAA in 1995 showed that in an en-route sector, the voice communication channel gets saturated, causing delay to airplanes passing through the sector and hence the arrival of these planes to an airport gets delayed [8]. Due to frequency congestion, controllers are often unable to adequately perform and meet restriction minima for airport arrivals. The procedures implied by the M&S concept will result in reduced frequency congestion, making the voice radio more available for time critical clearance delivery. As pointed out above, this will decrease the time of a transmission but also reduce the number of voice messages sent by controllers. Nonetheless, reduced radio communication will result in a decrease in both pilots and controllers errors.

When a pilot responds to a controller transmission with an incorrect readback of that transmission, this is called a readback error. If the controller does not detect or correct the readback error, this is called a hearback error. Readback and hearback errors as well as the pilot’s request for a repeat of all or part of the transmission are considered miscommunications.

Miscommunications result in increased frequency congestion and increased controller workload, as more communication is necessary to correct the misunderstandings. Moreover, miscommunications have the potential of narrowing the margins of safety to an unacceptable level.

The distribution of the readback errors as a function of the type of information in errors shows that altitude (and altitude restrictions) accounts for 19.5% of the readback errors, speed accounts for more than 33% of the readback errors and heading readbacks represent approximately 23% of the total number of readback errors. Other readback errors are represented by radio frequencies, route/position and altimeter.

The same study revealed that the number of readback errors doubles as clearances increase in complexity from 3 elements to 4. While clearances that contained four or more pieces of information made up only 26% of the readbacks, they accounted for 51% of the readback errors, found in an analysis of TRACON controller-pilot voice communication.

With respect to hearback errors, Cardosi et al (1996) show that 50% of the hearback errors involve speed instructions, whereas 21% of the readback errors represent altitude clearances. Frequency changes, heading and position instructions account for the rest of the readback errors.

5. Numerical Results

The previous chapter focused on identifying possible changes that will be applied to the CATS model, with respect to the M&S concept. Airborne technologies that will interact with AMSTAR have been considered (RNAV and auto throttles). Moreover, assumptions with respect to aircraft generation and surveillance support tools for ATCo have been considered. Nevertheless, risk benefits and risk penalties implied by the concept have been identified. All these would be translated, exploiting the structure of the CATS model, into the risk implications of the M&S concept.

All risk impacts were computed in Uninet, using both analytical conditioning and sample based conditioning of appropriate variables. As underlined in chapter 3, performing analytical conditioning is achievable under the assumptions used for non-parametric continuous/discrete BBNs.

5.1. Quantification of the assumptions

In order to assess the risk impacts of the M&S concept, firstly the risk implications of the assumptions have to be quantified. Namely, the impact of the aforementioned surveillance technology and aircraft generation assumptions needs to be quantified. As specified in the previous chapter, the surveillance technology is assumed to be at least primary radar and the aircraft is assumed to belong to the third or fourth generation.

In addition to the overall accident probability, other accident categories or relevant end events have been considered: loss of control in flight, collision in mid-air, collision with ground and CFIT. The impact of these assumptions on their probabilities is presented in Table 5.5:

Table 5.5 Percent reduction in accident rate due to assumptions (aircraft generation and surveillance technology), in CATS model, relative to CATS baseline.

Accident type	% reduction in accident rate
All Accidents	**20.7%**
Loss of control in flight	**18.8%**
Collision with ground	**18.3%**
Collision in mid-air	**9.5%**
CFIT	**27.7%**

As observed in the above table, aircraft generation and surveillance technology have the largest impact on controlled flight into terrain (CFIT). A 20.7 percent reduction is obtained in the overall accident probability.

As the aim of the study is to quantify the risk implications of the M&S concept, all further quantifications will be made relative to these assumptions.

5.2 Three approaches to quantification

Three quantifications of M&S in CATS are analyzed:

*1) **Take it to the Bank:** Risk impact of reduction in total transmission time*
*2) **Realistic:** Risk impact of M&S within the current CATS assumptions*
*3) **Stress test:** risk impact of M&S within CATS, under traffic doubling pessimistic scenario*

Impact of reduction in total transmission time

The first risk assessment was made by altering the CATS baseline (with assumptions) only with the addition of the reduction of total transmission time between the controller and the flight crew. As stated in the previous chapter, altitude instructions account for 16 percent of the total transmission time and similarly, speed instructions account for 14 percent. Hence, it is reasonable to assume a reduction of 30 percent in the total transmission time. This reduction in total transmission time has lead up to a decrease of 11.1 percent in the overall accident probability. Furthermore, as in the previous section, other accident categories or relevant end events have been considered: loss of control in flight, collision in mid-air, collision with ground and CFIT. The impact of the total transmission time reduction (30 percent) on their probabilities is presented in Table 5.6:

Table 5.6 Percent reduction in accident rate due to M&S induced reduction in total transmission time, in CATS model, relative to CATS baseline (with assumptions).

Accident Type	% reduction in accident rate
All accidents	**11.1%**
Loss of control in flight	**13.3%**
Collision with ground	**20.2%**
Collision in mid-air	**8%**
CFIT	**23.4%**

The largest impact of the air/ground communication is achieved by the CFIT accident type (23.4% reduction), followed by collision with ground (20.2%). This only illustrates that the corresponding communication reduction has the most significant influence on these two accident categories, with regard to all considered accident types.

Risk impact of M&S within the current CATS assumptions

The next quantification considered communication reduction, as well as influences on the base events (see Appendix G). The decrease in air/ground communication and the structure of the model will capture the effect of the communication reduction on both the crew and the controller error, not only on the communication errors. As stated in Section 3.3.2, whenever a base event in the FTs corresponds to a human error, it is linked to the corresponding human performance BBN. These influences on the base events will capture the impact of ADS-B (i.e. inadequate or lack of information from preceding aircraft), AMSTAR and AMSTAR coupled with auto throttles (i.e. poor manual flight control causes unstable approach) and reduction of air/ground communication. Where no objective quantifications were available, realistic assumptions have been made. All the assumptions are described in Appendix G; some of them are detailed below.

The base event "poor manual flight control causes unstable approach" is defined as an input to the aircraft's flight controls by flight crew, which destabilize the approach of becoming destabilized, such as high sink rate, deviation above or below the glide slope, speed too fast/ slow, or aircraft not aligned with the centre line to the runway. Therefore, given the assumption that AMSTAR is coupled with auto throttles, the probability of this base event is expected to decrease significantly. A 30 percent reduction of this probability was assumed.

Another affected base event is "poor automated systems management causes unstable approach", referring to situations in which the flight crew uses the flight management system inappropriately. Flight management system includes the auto pilot and auto throttles among others. When AMSTAR is coupled with the auto throttles, it is reasonable to assume that the probability of this event would decrease. A 10 percent reduction was assumed.

An additional influenced base event is "inadequate or lack of information from preceding aircraft". As in the merging in arrival streams operations, the aircraft receives ADS-B reports from the leading aircraft, a 50 percent decrease of this base event probability was assumed.

Another assumed change involved the "loss of communication" base events from ESD31 – Aircraft are positioned on collision course. Obviously a decrease in air/ground communication will consequently lead to a decrease in the loss of communication. In [9], the contributing factors to loss of communication are identified. Frequency congestion (3%) and readback/hearback errors with regard to frequency change (25%) are among the most common factors. Both probability factors are expected to decrease, given the decrease in air traffic communication and the reduction of the message length. It was assumed that the merging and spacing operations will imply a 10% decrease in the loss of communication probability.

As stated in the previous section, the altitude and speed instructions accounted for 29% of pilots' readback errors. Therefore, the inadequate/incorrect readback base events probabilities from ESD31 (Aircraft are positioned on collision course) were reduced with 29%.

The base event "strategic conflict" is defined as a separation infringement caused by unmodified flight plan requests. Furthermore, an ineffective air traffic flow and capacity management (ATFCM) denotes the failure of ATFCM to prevent strategic conflict developing into pre-tactical conflict. Both events are expected to encounter a decrease in probability during merging and spacing operations. A 20 percent decrease of the corresponding probabilities was assumed.

No risk penalties have been assumed, as this model reflects the M&S integration in the current traffic framework. Therefore, the existing separation buffers between aircraft are assumed for AMSTAR equipped aircraft in merging arrival streams. The resulting accident probability reductions are shown in Table 5.7:

Table 5.7 Percent reduction in accident rate as consequence of M&S protocols, in CATS, relative to CATS baseline (with assumptions).

Accident type	% reduction in accident rate
All Accidents	**14.4%**
Loss of control in flight	**16.1%**
Collision with ground	**26.3%**
Collision in mid-air	**14.8%**
CFIT	**28.7%**

These results demonstrate that the concept improves the current levels of safety, at current levels of traffic volume. Given all the corresponding changes, the overall accident probability is reduced by 14.4%. The largest percentage in reduction is achieved once more by collision with ground. This reflects that the risk benefits considered in this assessment had a significant impact on collision with ground.

Stress test: risk impact of M&S within CATS, under traffic doubling pessimistic scenario

Of course the goal of M&S is to enable an increase in volume, without an increase in the overall accident probability. In this section the risk impact of M&S in CATS is considered, where traffic volume is doubled, and pessimistic assumptions are made about the effect of this doubling on other base events. Where a clear negative effect could be anticipated, this effect was assumed to be large. This should be viewed as a stress-test of the M&S concept, not a realistic projection.

Therefore a corresponding projection of the M&S concept on the forecasted capacity increase has been considered further. The approach commenced with the previously developed model and considered the appropriate changes with respect to the increased capacity and hence, decreased spacing interval between aircraft. The first consideration is motivated by the fact that the concept is expected to preserve most of the identified risk benefits in an increased traffic scenario. The latter consideration is induced by the separation infringement increase corresponding to the reduced spacing interval between aircraft. However, it should be borne in mind that the enhanced crew and controller capabilities and situation awareness could lessen these probabilities.

The first obvious change was to double the traffic, as suggested by the increased capacity traffic forecast. Traffic is an influencing factor in the ATC human performance model. However, it should be noticed that the experts have assessed a negative correlation between the traffic and the ATCo error. Namely, the more aircraft under control, the less errors for the air traffic controllers.

The baseline probabilities for the base events "strategic conflict" and "ineffective air traffic flow and capacity management (ATFCM)" are left unchanged. This is motivated by the reduced aircraft spacing interval (which would increase the probabilities) and by the benefits of the M&S concept (which would decrease these probabilities). All the base event modifications implied by the previous risk assessment were left unchanged, as all refer to flight crew errors or airborne capabilities, which are not expected to change due to the increased traffic. The base events corresponding to controllers' errors are also left unchanged relative to the CATS baseline, since, according to the experts, the traffic does not negatively affect these errors. Nonetheless, the probability of "loss of communication" will be restored to the baseline value (current situation), as due to the increase of traffic volume, the probability of radio congestion and hence loss of communication will increase again.

Another base event influenced by the hypothesized traffic increase is "conflict in uncontrolled airspace". The base event refers to the airspace sectors which are not monitored by the air traffic controllers. Given the expected increased traffic density, a corresponding increase of the base event probability should be anticipated. As no data is available, a pessimistic assumption of doubling the probability has been chosen. The results are presented in Table 5.8.

Table 5.8 Percent reduction in accident rate as consequence of M&S protocols with doubling of traffic volume, in CATS, relative to CATS baseline (with assumptions).

Accident type	% reduction in accident rate
All Accidents	**6.9%**
Loss of control in flight	**9.7%**
Collision with ground	**11.5%**
Collision in mid-air	**8.3%**
CFIT	**12.1%**

The results show a decrease relative to the existing accident probabilities. This suggests that the M&S concept can improve the current levels of safety under a doubling of traffic volume. A corresponding reduction in risk is less than that shown in Table 5.6 owing to the pessimistic assumptions about the impact of traffic doubling.

This sort of stress testing requires a numerical weighing of risk benefits and risk penalties of the new M&S concept, and in turn, this illustrates the advantage of a system level risk model.

The last quantification aims to compare risk impact of M&S within CATS, under traffic doubling pessimistic scenario with the CATS baseline, under the same traffic doubling scenario. Once more, the assumptions regarding aircraft generation and surveillance technology will hold. Table 5.9 presents the obtained numerical estimates.

Table 5.9 Percent reduction in accident rate as consequence of M&S protocols with doubling of traffic volume, in CATS, relative to CATS with doubling the volume (and assumptions).

Accident type	% reduction in accident rate
All Accidents	**17.1%**
Loss of control in flight	**19.5%**
Collision with ground	**29.5%**
Collision in mid-air	**18.3%**
CFIT	**30.1%**

As expected, the results show a decrease relative to the "doubling the traffic volume" probabilities. It is noteworthy that this percent reduction in accident rate is higher to the percent reduction in the accident rate as a consequence of M&S protocols, relative to CATS baseline (with assumptions). This is due to the difference in the assumptions (see Appendix G). For doubling the traffic, without M&S, no reduction of total transmission time between aircrew and controller was assumed. Moreover, the considered flight crew errors will increase relative to CATS baseline and hence relative to the M&S protocols with doubling the traffic, in CATS. The same will hold for the ATCo errors. The main reasoning behind this assumption regards the increase of the overall transmission time, which increases both human errors.

However, it should be borne in mind that the last two risk impacts have been assessed relative to the CATS baseline and hence relative to the current infrastructure. Possible changes to the current aviation framework that might arise from inherent technical innovations and infrastructure changes will be described in the following chapter.

6. Future extensions

All the risk impacts assessed in the previous chapter were computed relative to CATS baseline. However, it should be borne in mind that CATS focuses on the risks in the current aviation framework and hence it is not designed to predict future risks. Consequently, one has to consider characteristics of the current system that might change in the coming years or features that are not considered in the current model development.

The need for transformation is inherent, as the current aviation framework will not meet future challenges. The existing use of ground-based navigational aids implies that aircraft flight paths are zigzag, thus less precise and inefficient in fuel consumption and time. Current reliance on ground-based radar surveillance means less efficient aircraft separation and therefore less capacity. The current communication approach is mostly single-channel and voice-based, relying on outdated analog technology.

In U.S., the governmental administrations are preparing for these transformational changes through the Next Generation Air Transportation System (NextGen) initiative. The concept is designed to address many of the most significant limitations to growth in the current air transportation system. These include runway capabilities and the aforementioned limitations of ground-based control of en-route and terminal airspace. NextGen is designed to increase system performance in the near term by improving the efficient use of the existing runways. The concept will include data link communications, network enabled weather and a system-wide information management and aircraft trajectory-based operations. The planned trajectories will be exchanged among system participants and automation will continuously analyze trajectories, taking into account aircraft state data and weather information. M&S concept is the second stage of development for the integration of automation for trajectory analysis and separation assurance. However, M&S currently relies on automation tools that work within the “static” route structure and airspace.

In NextGen, most communications will be made through digital data. Navigation will be satellite based, allowing for more precise flight paths, rather than dictated by the ground-based infrastructure. Tools to detect and avoid hazardous wake vortices will be developed and integrated. Surveillance will be also satellite based, providing situation awareness to both flight crew and controllers. The current ground-based radar system will be replaced by Global Positioning System (GPS). GPS is not only more accurate and reliable, but also cheaper to maintain. Moreover, the air traffic controllers will be able to manage the airspace efficiently using all available airspace and resources without any path restrictions, unlike the ground based radar approach.

ADS-B technology will be among the first implemented new systems. ADS-B uses GPS to broadcast the position and the intent of the aircraft. Furthermore, in the cockpit, pilots will also have access to information on weather, traffic and flight restrictions.

Since the late 1990s, aircraft equipped with ADS-B technology have been participating in an FAA test program in Capstone (southeastern Alaska). Preliminary estimates show that the accident rates for both general aviation and commercial carriers participating in the tests have been reduced with 40 percent when compared to aircraft operating elsewhere in Alaska. Furthermore, delivering corporation UPS is currently using ADS-B technology. This has allowed UPS to reduce emissions by 34 percent and noise by 30.

As part of near-term integration of NextGen into the national airspace system, ADS-B will next be installed at important hubs by 2010, including the Gulf of Mexico, Louisville, Juneau and Philadelphia. By 2014, it is planned to use ADS-B for oceanic in-trail maneuvers. Moreover, aircraft will be required to be equipped with ADS-B by 2020. Besides United States, Australia, China, Canada and Sweden have intense programs to implement ADS-B as the main surveillance technology for the used airspace.

In addition to the intensive NextGen program, parallel efforts have been put into the transformation and the modernization of air transport system. In 2005, NASA carried out a Small Aircraft Transportation System (SATS) demonstration project. The project aimed for a new generation of safe and affordable small aircraft, which would take the pressure off busy airports. Moreover, it will meet the forecasted increasing need for on-demand operations. With this respect, one can expect a significant increase in the number of very light jets (VLJ) and even unmanned aerial vehicles (UAV).

Additionally, NASA is already designing and developing engine and airframe technologies that provide a significant cut in emissions, such as environmentally sound aircraft configurations that burn less fuel and generate less noise. Moreover, the implementation of the continuous descent approach will result in less fuel consumption and reduced noise. It is forecasted that aviation noise and emissions are likely to grow by 140 to 200 percent under future growth scenarios if no action is taken with this respect [22].

Nonetheless, it should be borne in mind that system transformation not only involves technological innovations, but also changes in the organizational structure, processes and strategies. It is acknowledged that grafting new technology onto obsolete policies and business practices will not succeed.

Airport taxiways and runways reconfigurations are expected in order to enable high-capacity traffic operations. Airborne separation standards will be reduced, as a result of new aircraft capabilities, enhanced surveillance and navigation performance. Significant changes in the current infrastructure are expected as well. To meet future demands, FAA plans to hire and train nearly 17,000 traffic controllers over the next decade. The training and certification requirements for flight crew members and air traffic controllers are expected to change. Moreover, maintenance regimes are expected to adjust to the forecasted increased demands. Nonetheless, new security policies can be introduced.

As mentioned in the introduction, both technological innovations and infrastructure changes will aim to meet growing demands but also to actively address risk and anticipate potential safety problems, in order to prevent accidents.

7. Conclusions

As previously highlighted, one of the main motives for introducing automation and corresponding procedures is the forecasted need for the airspace increase. There is also a significant efficiency pressure, given that relative short delays can translate into very large financial losses. In 2006, every minute of aircraft delay cost the U.S. industry 60.46$, for an annual system total of more than 8 billion [21]. However, in addition to increasing capacity, such a concept must also meet other system performance targets in areas such as noise, emissions, safety and security.

Even given the current very low accident rate in commercial and private aviation, the need remains to strive for even greater safety levels. Therefore, the need for improvement should be driven by the desire to improve efficiency without sacrificing current levels of safety. The growing demand for aviation, the development of new airborne and ground-based technologies and security and environmental concerns will ultimately require a new approach for the aviation system, as described in the previous chapter.

In conclusion, one cannot think in terms of "safety versus growth"; the desire is to achieve both of them. As mentioned in the introduction, designing for increased volume must be coupled with designing for decreasing risk.

This study represents an attempt to use the CATS safety model to quantify the risk impact of new Merging and Spacing (M&S) protocols. In line with the above discussion, designing systems for greater volume must go hand in hand with designing for lower risk. System level risk models allow total risk to be engineered rather than just undergone.

Taking into account the features detailed in chapter 4 and using the current calibration of the model, it can be predicted that the M&S system, if implemented into the current aviation system modeled by CATS, would lead to a 14.4% reduction in the fatal accident rate, per flight. It is noteworthy that CATS model development has not finished and final numerical estimates will be derived once the model will reach its final status.

Moreover, it has been shown that despite the limitations to the current airspace framework, potential users can use the model, by appropriately altering CATS baseline scenario, to predict various future risks. This study focused on altering the baseline scenario with respect to the air/ground communication reduction, AMSTAR and ADS-B. However, a thorough analysis of appropriate changes regarding the two interacting technologies, RNAV and auto throttles, would be advisable. With this respect, careful assessments should be made.

It is well to emphasize once more that the CATS model focuses on risk in the *current* aviation system. The model is not designed to predict the risk in the future. Many features in the current system will change in the coming years, including the mix of aircraft, the type of trips, the enabling technologies, the maintenance regimes, and the training and certification of flight crew and air traffic controllers. While a quantitative risk model for the civil aviation system for the year 2020 is beyond the current state of the art, a model like CATS allows assessing the impact of changes against a current baseline.

The CATS risk model is configured to quantify risks in the current situation, anno 2008. It does not directly predict risk 20 years hence, as many changes in the total system may not be anticipated. However, by showing how the new M&S protocols would impact the CATS model, we may assess the risk reduction which the M&S protocols would have on the current situation.

Finally, it should be borne in mind that CATS ultimately represents an objective assessment of principal causes of aviation system accidents and hence it has its own limitation. The main reason is the impossibility of representing in objective quantifiable units important factors such as traffic complexity, safety culture or time pressure. Nevertheless, CATS represents the first model that successfully combines technical failures, human errors and environmental and management influences as causal factors of an accident.

Bibliography

1. A.L.C.,Roelen; B.A., van Doorn; J.W.,Smeltink; M.J.Verbeek; R., Wever Quantification of Event Sequence Diagrams for a causal risk model of commercial air transport.
2. A.M.Hanea, D. Kurowicka, R.M.Cooke Hybrid method for quantifying and analyzing Bayesian Belief Nets.
3. D. Kurowicka, R.M.Cooke Distribution-free continuous Bayesian Belief Nets, Proceedings of the Mathematical Methods in Reliability Conference, June 2004.
4. B.Ale et al, Causal Model for Air Transport Safety – Modified Seventh Interim report, March 2007.
5. http://www.airlines.org/economics/specialtopics/ATC+Delay+Cost.htm
6. Sarter, N.B. (1996). Cockpit Automation: From Quantity to Quality, From Individual Pilot to Multiple Agents. In R. Parasuraman and M. Mouloua (Eds.), *Automation and Human Performance: Theory and Applications* (pp. 267-280). Hillsdale, NJ: LEA.
7. www.airdisaster.com
8. User benefits of two-way data link ATC communications: Aircraft delay and flight efficiency in congested en-route airspace FAA (1995)
9. Es, Gerard van Air-ground communication study: An analysis of pilot controller occurrences, Eurocontrol 2004
10. www.eurocontrol.int/eec/public/stand.page/conf .papers
11. Prinzo, O. Veronika , Hendrix, Alfred M. The outcome of ATC message complexity on pilot readback performance, FAA 2006
12. http://www.mitre.org/news/digest/aviation/01_05/a_targets_eases.html
13. http://www.ikp.liu.se/hfn/Publications/Proceedings2006.pdf
14. http://en.wikipedia.org/wiki/Air_traffic_control
15. Cardosi, Kim, Falzarano, Paul, Sherwin, Han Pilot-Controller Communication Errors: An analysis of aviation safety reporting systems (ASRS) reports
16. Burki-Cohen, Judith An analysis of tower (ground) controller-pilot voice communication
17. Cardosi, Kim, Brett, Bryan, Sherwin, Han An analysis of TRACON (Terminal Area Approach Control) controller-pilot voice communications
18. Morrow, Daniel, Lee, Alfred, Rodvold, Michelle Analysis problems in Routine controller-pilot communication
19. FAA Aerospace Forecasts Fiscal Years 2007-2020, US Department of Transportation, Federal Aviation Administration, Aviation Policy and Plans.
20. Civil Aviation Safety Data, Inspectie Verkeer en WaterStaat. Paostbus 575, 2130 AN Hoofddorp, www.ivw.nl
21. A.L.C.Roelen, G.B. van Baren, J.W. Smeltink, P.H.Lin, O.Morales Napoles A generic flight crew performance model for application in a causal model of air transport safety
22. https://employees.faa.gov/org/linebusiness/ato/resources/fact_sheets/pdfs/NextGen_Brochure.pdf

23. Barmore, Bryan E.; Abbott, Terence S.; Krishnamurthy, Karthik Airborne-Managed Spacing in Multiple Arrival Streams.
24. Barmore, Bryan E. Airborne Precision Spacing: A Trajectory-Based Approach to Improve Terminal Area Operations.
25. Barmore, Bryan E.; Abbott, Terence S.; Capron, William R. Evaluation of Airborne Precision Spacing in a Human-in-the-Loop Experiment
26. Barhydt, Richard; Eischeid, Todd M.; Palmer, Michael T.; Wing, David J. Regaining Lost Separation in a Piloted Simulation of Autonomous Aircraft Operations
27. Ballin, Mark G.; Hoekstra, Jacco M.; Wing, David J.; Lohr, Gary NASA Langley and NLR Research of Distributed Air/Ground Traffic Management
28. Hoffman, Eric; Ivanescu, Dan; Shaw, Chris; Zeghal Karim; Analysis of Constant Time Delay Airborne Spacing Between Aircraft of Mixed Types in Varying Wind Conditions
29. Boursier, Ludovic; Favennec, Bruno; Hoffman, Eric; Trzmiel, Aymeric; Vergne, Grancois; Zeghal, Karim Merging Arrival Flows Without Heading Instructions
30. Wang, Ganghuai; Hammer, Jonathan Analysis of an Approach Spacing Application
31. Oseguera-Lohr, Rosa M.; Lohr, Gary W.; Abbott, Terence S., Eischeid, Todd M. Evaluation of Operational Procedures for Using a Time-Based Airborne Interarrival Spacing Tool
32. Baxley, Brian T.; Barmore, Bryan; Abbott, Terence S.; Capron, William R. Operational Concept for Flight Crews to Participate in Merging and Spacing of Aircraft
33. Peters, Mark E.; Ballin, Mark G.; Sakosky, John S. A Multi-Operator Simulation for Investigation of Distributed Air Traffic Management Concepts
34. Krishnamurthy, Karthik; Barmore, Bryan; Bussnik, Frank Airborne Precision Spacing in Merging Terminal Arrival Routes: a Fast-Time Simulation Study
35. Bussnik, Frank J.L.; Doble, Nathan A.; Barmore, Bryan E.; Singer, Sharon A Fast-Time Simulation Environment for Airborne Merging and Spacing Research
36. Kopardekar, Parimal; Battiste, Vernol; Johnson, Walter; Mogford, Richard; Palmer, Everett; Smith, Nancy; D'Arcy, Jean Francois; Helbing, Katrin; Mafera, Paul; Lee, Paul; Mercer, Joey; Prevot, Thomas; Shelden, Stephen Distributed Air/Ground Traffic Management: Results of Preliminary Human-in-the-Loop Simulation
37. Oseguera-Lohr, Rosa M.; Lohr, Gary W.; Abbott, Terence S.; Nadler, Eric D.; Eischeid, Todd M. Evaluation of a Tool for Airborne-Managed In-Trail Approach Spacing
38. http://www.faa.gov/data_statistics/aviation/aerospace_forecasts/2007-2020/media/FORECAST%20BOOK%20SM.pdf

Appendix A

Event Sequence Diagrams:

1	Aircraft system failure
2	ATC event
3	Aircraft handling by flight crew inappropriate
4	Aircraft directional control related systems failure
5	Operation of aircraft systems by flight crew inappropriate
6	Aircraft takes off with contaminated wing
7	Aircraft weight and balance outside limits
8	Aircraft encounters performance decreasing windshear after rotation
9	Single engine failure
10	Pitch control problem
11	Fire on board aircraft
12	Flight crew member spatially disorientated
13	Flight control system failure
14	Flight crew incapacitation
15	Anti-ice system not operating
16	Flight instrument failure
17	Aircraft encounters adverse weather
18	Single engine failure
19	Unstable approach
21	Aircraft weight and balance outside limits
23	Aircraft encounters windshear during approach/landing
25	Aircraft handling by flight crew during flare inappropriate
26	Aircraft handling by flight crew during roll inappropriate
27	Aircraft direction control related systems failure
28	Single engine failure
29	Thrust reverser failure
30	Aircraft encounters unexpected wind
31	Aircraft are positioned on collision course
32	Incorrect presence of aircraft/vehicle on runway in use
33	Cracks in aircraft pressure cabin
35	Flight crew decision error/operation of equipment error

Appendix B

Human Performance models

1. Flight Crew performance Model:

- **First Officer Experience –** Total numbers of hours flown (all type) since the pilot's license obtaining by the first officer.
- **First Officer Training –** Number of days passed since last recurrence training for first officer.
- **Fatigue –** Standford Sleepiness Scale. 1-"feeling active and vital; wide awake", 2- … 7- "almost in reverie; struggle to remain awake".
- **Captain Training -** Number of days passed since last recurrence training for captain.
- **Captain Experience -** Total numbers of hours flown (all types) since the pilot's license obtaining by the captain.
- **Captain UnSuitability –** Likelihood that the captain fails a proficiency check test.
- **First Officer UnSuitability -** Likelihood that the first officer fails a proficiency check test.
- **Weather –** Rainfall rate (mm/hr).
- **Delta Language –** Difference in mother tongue between captain and first officer.
- **Crew UnSuitability –** Number of captains or/and first officers failing their proficiency check test per 10,000.
- **Aircraft Generation –** Aircraft generation is a scale from 1 to 4, where 4 is the most recent generation of aircrafts (the list of aircraft generation can be found in [21]):
    - 1 – aircraft typically designed in the 1950s;
    - 2- aircraft typically designed in the 1960s and 1970s;
    - 3 - aircraft typically designed in the 1980s and 1990s;
    - 4 – the most recent generation of aircraft.
- **Workload –** Number of times the crew has to refer to the abnormal/emergency procedures section of the aircraft operation manual during flight.
- **Flight Crew Error –** The likelihood that the flight crew makes an unrecovered error that is potentially hazardous for the safety of the flight, per 100,000 flights.

2. Air Traffic Controller (ATCo) Model:

- **Traffic –** Number of aircraft (any type) simultaneously under control.
- **ACTo Experience –** Number of years working as an ATCo in the same position.
- **Man-Machine Interface –** It describes the available technology for the ATCo:
    - 1 – using radio only;
    - 2 – using radio and primary radar;
    - 3 – radio, primary radar and secondary radar;

    - 4 – using radio, primary and secondary radar and additional tools (e.g. SMGCS, STCA);
- **Communication-Coordination –** 2 states variable:
    - 1 **–** The communication with other ATCos takes place in the same room;
    - 2 – The communication with other ATCos does not take place in the same room.
- **Visibility procedures –** 5 states variable:
    - 1 – normal visibility operations;
    - 2 – reduced visibility operations;
    - 3 – low visibility operations;
    - 4 – limited visibility conditions
    - 5 – imply severe separation limits.

3. **Maintenance Model:**

- **Fatigue –** Standford sleepiness scale (see flight crew performance model);
- **Experience –** Number of years in current position;
- **Workload –** Estimated delay in release of the aircraft;
- **SO Time -** Time available to transfer a job;
- **Workload condition –** Whether the work is performed at the ramp or in the hangar (outside or inside).

Appendix C

1. Accident categories:

Take-off
Fire in flight
Loss of control in flight
Engine failure in flight
Landing
Collision
Structural accident
CFIT

2. End events:

Runway overrun
Runway veer-off
Collision with ground
In-flight break up
Aircraft lands off runway
Aircraft continues landing roll damaged
Aircraft damaged
Collision in mid-air
Collision on runway

Appendix D

List with the definitions of the initiating events for the ER and AL ESDs

1. ESD11 – Fire on board

A situation where a combustible substance on-board the aircraft is burning, e.g. aircraft's payload, systems, or interior. Indicators of a fire are visible flame, but also visible smoke or burning smell.

2. ESD12 – Flight crew spatially disoriented

Flight crew suffers spatial disorientation, i.e. has inadequate visual information or fails to attend to or properly interpret available information regarding the airplane's pitch, roll or yaw angle or rate of rotation.

3. ESD13 – Flight control system failure

A failure of any part of the control system, i.e. Control Surface, Autopilot, Auto throttle, Thrust Reverser.

4. ESD14 – Flight crew incapacitation

An occurrence where one or more flight crew are unable to perform an in-flight duty as result of reduced medical fitness, e.g. illness, depressurization of flight deck or presence of toxic gas from fire in flight deck.

5. ESDS15 – Anti-ice/de-ice system not operating

Ice accretion on the aircraft's outside structure, i.e. fuselage, wings, tail, and flight control surface

6. ESD16 – Flight instrument failure

Failure of flight instrument to correctly display airspeed or altitude of the aircraft. In the case of dual instruments and/or if a standby instrument is available, even a failure of only one of the instrument to correctly display is considered to be a 'flight instrument failure.

7. ESD17 – Aircraft encounters adverse weather

Aircraft encounters adverse weather - An encounter with severe turbulence that results in occupant injuries, an aircraft upset or structural damage to the aircraft as a result of overstress of the aircraft structure.

8. ESD18 – Single engine failure

A significant loss of thrust from one of the aircraft's propulsion system, including cases where the engine detaches from the aircraft.

9. ESD19 – Unstable approach

Unstable approach is when one or more of the parameters set out by the operator of the aircraft are incorrect. These parameters include, correct glide path; small changes in heading/ pitch; speed between Vref and Vref+20knots; correct landing configuration; sink rate is no greater than 1000ft/ min; power setting appropriate for the aircraft configuration; all briefings and checklists have been conducted; approach type specific (ILS approaches, Cat. II or III ILS approach, circling approach).

10. ESD 21 - Aircraft weight and balance outside limits during approach

Aircraft's centre of gravity or the aircraft's weight differs from the flight crew's expectation such that flight crew has to take additional action to maintain control during approach.

11. ESD23 – Aircraft encounters windshear during approach

An abrupt change in wind direction and velocity. A particularly hazardous type is a downburst or microburst.

12. ESD25 – Aircraft handling by flight crew during flare inappropriate

A landing flare is a sub phase of landing and starts when the transition from nose-low to nose-up attitude occurs up until the point of touchdown. If pilot does not arrest the rate of descent significantly during the landing flare, the aircraft will touch down hard. A flare that starts from a stabilized condition at the runway threshold but the maneuver itself is conducted inappropriately. A stabilized condition at the runway threshold is defined as where the aircraft is not more than 10 ft above or below the prescribed height and not more than 10kts faster or slower than the target (or bug) speed.

13. ESD26 – Aircraft handling by flight crew during landing roll inappropriate

A touchdown is made with a correct speed and sink rate, but due to an action by the crew during landing roll, control of the aircraft is lost or maximum braking is not achieved. Inappropriate aircraft handling includes inappropriate use of rudder and aileron, inappropriate use of the steering tiller, delayed operation of deceleration devices such as life dumper, thrust reverser and wheel brakes and inappropriate differential braking.

14. ESD27 – Aircraft directional control related system failure during landing

Failure of any part of the aircraft's systems that affects the directional controllability of the aircraft during the landing roll. Included are failures of the aileron and aileron controls, rudder and rudder controls, tires and landing gear.

15. ESD28 - Single engine failure during landing

Any failure of one of the systems that correspond with the ATA codes between 6100 and 6197 or between 7100 and 8097.

16. ESD29 - Thrust reverse failure

A failure of system ATA 7830 reverser for aircraft with jet propulsion and a failure of system ATA 6120 propeller control for aircraft with propeller propulsion. Only technical malfunction of the thrust reverser system are considered.

17. ESD30 – Aircraft encounters unexpected wind

Aircraft encounters significant unexpected cross wind, gusting winds and/ or turbulence that flight crew need to take additional action to maintain control.

18. ESD31 – Aircraft are positioned on collision course

Two airborne aircrafts are positioned such that their trajectories, if unaltered, will bring the aircraft closely together leading to a risk for collision.

19. ESD33 – Cracks in aircraft pressure cabin

Presence of crack in an aircraft pressure boundary, which are, or should have been, detected during maintenance or line checks

20. ESD35 – Flight crew decision error/operation of equipment error (CFIT)

Any decision error or operation of equipment error that results in a deviation of the aircraft's flight path from a previously established safe route.

Appendix E

List of the end event nodes in the influenced ESDs

Code	End events	Probability	Unit	Definition
ER17d1-02	Collision with ground	4.42E-09	per flight	After encounter with adverse weather, flight crew fail to maintain control of the aircraft and it collides with the ground.
AL19d1-01	Collision with ground	3.21E-07	per flight	After an unstable approach and the flight crew fail to initiate or execute a missed approach, the flight crew is unable to maintain control and the aircraft collides with the ground.
AL19f1-02	Runway overrun	1.98E-07	per flight	After an unstable approach and the flight crew fail to initiate or execute a missed approach, the aircraft touchdowns long/ fast and flight crew are not able to halt to aircraft before it leaves the end of the runway. The aircraft overruns.
AL19h1-04	Runway veer-off	3.76E-08	per flight	After an unstable approach and the flight crew fail to initiate or execute a missed approach, the aircraft touchdowns with excessive sink rate and suffers a structural failure. The flight crew is unable to maintain control and the aircraft veers off the runway.
AL19e5-08	Collision with ground	5.01E-08	per flight	After an unstable approach and a missed approach executed, the flight crew is unable to maintain control and the aircraft collides with ground.
AL19f4-09	Aircraft lands off runway	7.52E-09	per flight	After an unstable approach and a missed approach executed, the flight crew maintain control but there is no sufficient fuel for the next approach. The aircraft lands off the runway.
AL23f1-01	Runway veer-off	1.55E-08	per flight	After a windshear encounter and touching down with a high sink rate, the aircraft is damaged and directional control is lost. Aircraft exits off the side of the runway.
AL23f3-04	Runway overrun	6.59E-09	per flight	After windshear encounter and touching down long or fast, the aircraft is unable to stop before it leaves the end of runway.
AL30c1-01	Runway veer-off	5.76E-08	per flight	After encounter with unexpected wind during landing, the flight crew fails to maintain control of the aircraft. The aircraft veers off the runway.
AL30d1-02	Runway overrun	2.26E-08	per flight	After encounter with unexpected wind during landing, the flight crew maintains control but is not able to achieve maximum braking. The aircraft overruns.

Code	End event	Probability	Units	Definition
ER31d1-01	Collision in Mid-Air	3.36E-08	per flight	When aircraft are positioned on collision course, ATC and flight crew both fail to resolve the conflict and aircraft collides in mid air.
AL35e1-01	Collision with ground	1.17E-08	per flight	Imminent CFIT is not detected by GPWS (Ground Proximity Warning System), and hence no timely recovery possible. Aircraft collides with ground.
AL35f1-02	Collision with Ground	3.69E-09	per flight	Imminent CFIT is detected by GPWS, flight crew are warned but fail to executed appropriate GPWS maneuver in time. Aircraft collides with ground.

Appendix F

Sensitivity analysis for all the end nodes that might result in an accident, ordered by rank correlation:

Predicted variable	Base variable	Product moment correlation	Rank correlation	Correlation ratio
OUT_TOERALAccident	AL19d1_01	0.9686	0.5033	0.9434
OUT_TOERALAccident	AL19h1_04	0.7549	0.4963	0.6086
OUT_TOERALAccident	AL19f1_02	0.6843	0.4929	0.4757
OUT_TOERALAccident	AL19h2_05	0.5804	0.4949	0.3558
OUT_TOERALAccident	AL25d2_02	0.4345	0.4269	0.2157
OUT_TOERALAccident	AL26c1_01	0.3071	0.3379	0.1524
OUT_TOERALAccident	AL35f1_02	0.3056	0.4013	0.105
OUT_TOERALAccident	AL32d1_01	0.2914	0.3748	0.0868
OUT_TOERALAccident	ER18e5_07	0.2713	0.3633	0.0747
OUT_TOERALAccident	AL19f4_09	0.2217	0.4553	0.0603
OUT_TOERALAccident	ER14c1_01	0.1967	0.3735	0.0486
OUT_TOERALAccident	AL25f1_03	0.1389	0.4149	0.0254
OUT_TOERALAccident	ER16c1_01	0.1585	0.4174	0.0251
OUT_TOERALAccident	ER15e1_01	0.1481	0.3729	0.0235
OUT_TOERALAccident	ER18e1_02	0.0806	0.3563	0.0234
OUT_TOERALAccident	AL25d1_01	0.1523	0.4138	0.0232
OUT_TOERALAccident	AL26d1_02	0.113	0.3226	0.0215
OUT_TOERALAccident	ER21c1_01	0.1423	0.405	0.0203
OUT_TOERALAccident	ER31d1_01	0.1157	0.3101	0.0134
OUT_TOERALAccident	AL19e5_08	0.0725	0.373	0.0111
OUT_TOERALAccident	AL30c1_01	0.0741	0.1153	0.0082
OUT_TOERALAccident	AL30d1_02	0.0506	0.1492	0.0073
OUT_TOERALAccident	TO05e1_01	0.0794	0.3716	0.0063
OUT_TOERALAccident	AL35e1_01	0.0722	0.1355	0.0052
OUT_TOERALAccident	ER17d1_02	0.0527	0.2035	0.0028
OUT_TOERALAccident	AL27c1_01	0.0439	0.2874	0.0026
OUT_TOERALAccident	ER12c1_01	0.0505	0.3741	0.0025
OUT_TOERALAccident	TO03d4_05	0.0343	0.1971	0.002
OUT_TOERALAccident	TO02d1_01	0.0443	0.0849	0.002
OUT_TOERALAccident	TO10d1_01	0.0352	0.3374	0.0012
OUT_TOERALAccident	TO03d1_01	0.0334	0.1752	0.0011
OUT_TOERALAccident	AL29c1_01	0.033	0.1126	0.0011
OUT_TOERALAccident	ER18d1_01	0.0243	0.3071	0.001
OUT_TOERALAccident	TO32d1_01	0.023	0.3133	0.001
OUT_TOERALAccident	TO05e7_07	0.0192	0.2735	0.0008

Predicted variable	Base variable	Product moment correlation	Rank correlation	Correlation ratio
OUT_TOERALAccident	TO10f1_03	0.0186	0.3084	0.0007
OUT_TOERALAccident	TO03e1_02	0.0193	0.2031	0.0006
OUT_TOERALAccident	TO10d4_05	0.0222	0.3289	0.0005
OUT_TOERALAccident	TO02e1_02	0.0211	0.0428	0.0004
OUT_TOERALAccident	TO09f1_03	0.0124	0.1421	0.0002
OUT_TOERALAccident	ER13c1_01	0.0143	0.2871	0.0002
OUT_TOERALAccident	TO04e1_02	0.0135	0.2267	0.0002
OUT_TOERALAccident	AL28c1_01	0.0153	0.2047	0.0002
OUT_TOERALAccident	TO01e1_02	0.0072	0.1929	0.0001
OUT_TOERALAccident	TO07d1_01	0.0096	0.088	0.0001
OUT_TOERALAccident	AL28d1_02	0.0114	0.1499	0.0001
OUT_TOERALAccident	AL23f1_01	0.0093	0.056	0.0001
OUT_TOERALAccident	AL23f2_02	0.0104	0.0562	0.0001
OUT_TOERALAccident	TO09e1_02	0.0085	0.1442	0.0001
OUT_TOERALAccident	TO04d4_05	0	0	0
OUT_TOERALAccident	TO08d1_01	-0.0008	0.0157	0
OUT_TOERALAccident	TO05f1_02	0	0	0
OUT_TOERALAccident	ER11e1_01	0.0017	0.2939	0
OUT_TOERALAccident	TO04d1_01	0.0013	0.1962	0
OUT_TOERALAccident	TO04f1_03	0.0001	0.1462	0
OUT_TOERALAccident	AL29d1_02	0.0036	0.152	0
OUT_TOERALAccident	ER33c1_01	0.0003	0.2529	0
OUT_TOERALAccident	TO01d1_01	-0.0038	0.2247	0
OUT_TOERALAccident	AL23f3_04	0.0009	0.0186	0
OUT_TOERALAccident	TO09d1_01	0.0028	0.1065	0
OUT_TOERALAccident	TO09d4_05	0.0019	0.1474	0

Appendix G

List of base events of the 6 considered ESDs influenced by M&S:

21. ESD17 – Aircraft encounters adverse weather

Aircraft encounters adverse weather - An encounter with severe turbulence that results in occupant injuries, an aircraft upset or structural damage to the aircraft as a result of overstress of the aircraft structure.

- **Inadequate or lack of (weather) information from preceding aircraft** (per severe clear air turbulence) - can be reduced, due to ADS-B weather reports, with 50%
- **Flight crew fails to obtain weather reports** (per unfavorable weather condition) - can be reduced, due to ADS-B weather reports, with 20%

22. ESD19 – Unstable approach

Unstable approach is when one or more of the parameters set out by the operator of the aircraft are incorrect. These parameters include, correct glide path; small changes in heading/ pitch; speed between Vref and Vref+20knots; correct landing configuration; sink rate is no greater than 1000ft/ mins; power setting appropriate for the aircraft configuration; all briefings and checklists have been conducted; approach type specific (ILS approaches, Cat. II or III ILS approach, circling approach).

- **Poor manual flight control causes UA** (An input to the aircraft's flight controls by flight crew results in the approach becoming destabilized, such as high sink rate, deviate above or below the glide slope, speed too fast/ slow, or aircraft not aligned with the centre line to the runway, per landing) – can be reduced, due to AMSTAR (speed guidance technology) coupled with auto throttles and RNAV, with 30%
- **Improper control exchange (**An exchange of control of the aircraft occurs at an inappropriate time during the approach or following an exchange of control, the flight crew are unsure of their roles, per landing**) -** can be reduced, due to AMSTAR coupled with auto throttles, with 10%
- **Poor automated system management causes UA** (Flight crew use the flight management system inappropriately. Flight management system includes the Autopilot and auto throttle systems among others) - can be reduced, as AMSTAR would provide the speed input to auto throttles or autopilot, with 10%.

23. ESD23 – Aircraft encounters windshear during approach

An abrupt change in wind direction and velocity. A particularly hazardous type is a downburst or microburst.

- **Failure of ATC to advise the pilot (**ATC fails to advise the flight crew that there is a windshear**,** per windshear on landing with LLWAS (low-level wind shear alert system) installed**) –** can be reduced/increased, due to reduced ATCo error with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

24. ESD30 – Aircraft encounters unexpected wind

Aircraft encounters significant unexpected cross wind, gusting winds and/ or turbulence that flight crew need to take additional action to maintain control.

- **ATC fails to report weather to pilot** (per severe wind condition) **–** can be reduced/increased, due to reduced ATCo error with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Pilot fails to calculate wind correctly (**per severe wind condition**) –** can be reduced due to the M&S protocol (given the technology requirements for M&S, it would be very unlikely that the pilot would ever have to compute the wind, hence the probability of this failure would be very small) with **50**%.

25. ESD31 – Aircraft are positioned on collision course

Two airborne aircrafts are positioned such that their trajectories, if unaltered, will bring the aircraft closely together leading to a risk for collision.

- **Strategic conflict (**Unmodified flight plan requests would lead to separation infringement, per flight**) –** can be reduced/increased

  ↓**20** % (current traffic with M&S)
  Doubled (doubled traffic with M&S) – pessimistic scenario
  Doubled(doubled traffic without M&S)

- **Ineffective air traffic flow and capacity management** (Failure of air traffic flow and capacity management (ATFCM) to prevent strategic conflict developing into pre-tactical conflict, per strategic conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **No ATC planning** (No attempts are made to identify pre-tactical conflicts before they reach the Tactical Controller, per pre-tactical conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Planning controller failure to recognize the conflict** (Planning Controller obtains correct flight information but fails to recognize medium-term conflict. This includes failure of MTCD if present conflict, per pre-tactical conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Planning controller misjudgment of conflict prevention** (Planning Controller aware of the conflict but misjudges the traffic situation and results in an inadequate separation plan, per pre-tactical conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Inadequate planning controller coordination** (Planning Controller fails to coordinate with other sectors, resulting in failure to implement planned traffic synchronization, per pre-tactical conflict) – can be reduced/increased with

↓**10**% (current traffic with M&S)
↓**10**% (doubled traffic with M&S)
↑**20**% (doubled traffic without M&S)

- **Planning controller failure to alert tactical controller to conflict** (Planning Controller fails to inform Tactical Controller of a conflict, per pre-tactical conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **ATCo failure to recognize conflict** (Tactical Controller obtains adequate flight information but fails to recognize the conflict, per plannable conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **ATCo misjudgment in tactical separation** (Tactical Controller recognizes the conflict, but misjudges the traffic situation and hence makes incorrect clearances or separation instructions to the aircraft, per plannable conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Inadequate ATCo coordination** (Tactical Controller fails to coordinate with other controllers, resulting in incorrect clearances or separation instructions, per plannable conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Inadequate ATCo transmission of instructions** (Inadequate transmission of instruction from ATCO, e.g. incorrect clearance, late clearance and unclear phraseology, per plannable conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Loss of communication** (Communication between ATCO and pilot is lost due to technical failure or human error, per plannable conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  No change (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Inadequate pilot response to ATC** (Flight crew fail to follow the clearances or separation instructions, per plannable conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10%** (doubled traffic with M&S)
  ↑**10**% (doubled traffic without M&S)

- **Inadequate ATCo transmission of instructions** (inadequate transmission of instruction from ATCO that leads to a vertical deviation of the aircraft, per flight) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Pilot handling error** Vertical deviation of aircraft due to pilot handling. This also includes cases of correct readback followed by incorrect action, failures to follow SID or climb/ descent without clearance., per flight) – can be reduced, due to RNAV, with 10%

- **ATCo failure to recognize conflict** (ATCO fails to recognize the unplannable conflict in time to issue separation instructions, per unplannable conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Inadequate ATCo transmission of instructions** (Inadequate transmission of instruction for an unplannable conflict from ATCO results in failure to maintain separation, per unplannable conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Loss of communication** (Communication between ATCO and pilot is lost during an unplannable conflict due to technical failure or human error, per unplannable conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  No change (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Inadequate pilot response to ATC** (Flight crew fail to follow the clearances or separation instructions, per unplannable conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10%** (doubled traffic with M&S)
  ↑**10**% (doubled traffic without M&S)

- **Trajectory instructions result in conflict** (Trajectory instructions from ATCO create a conflict that was not previously present, per flight) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Ineffective tactical separation of ATCo induced conflict (**ATCO does not recognise or resolve the conflict they have created, per ATCo induced conflict**) –** can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Conflict in uncontrolled airspace (**A conflict occurs in uncontrolled airspace where separation is the responsibility of the pilot, per flight**) –** can be reduced/increased with

  ↓**20%**(current traffic with M&S**)**
  Doubled (doubled traffic with M&S**) –**pessimistic scenario
  Doubled (doubled traffic without M&S**)**

- **Inadequate traffic information from ATCo** (Pilot receives the necessary traffic information for an conflict in controlled airspace but fails to maintain separation, per unmanaged conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Inadequate ATCo transmission of information** (Inadequate transmission of traffic information prevents the pilot maintaining separation in uncontrolled airspace, per unmanaged confict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  No change (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Loss of communication** (Communication between ATCO and pilot is lost during a conflict in uncontrolled airspace due to technical failure or human error, per unmanaged conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  No change (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Inadequate separation by pilot** (Pilot receives the necessary traffic information for an conflict in controlled airspace but fails to maintain separation, per unmanaged conflict) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10%** (doubled traffic with M&S)
  ↑**10**% (doubled traffic without M&S)

- **ATCo fails to recover separation in time** (ATCO is informed by other ATCO of a conflict but fails to resolve it in time, per separation loss) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Other aircraft effectively invisible** (The other aircraft cannot be seen from the cockpit, per involvement) – can be reduced, due to M&S cockpit display traffic information with 50%

26. ESD35 – Flight crew decision error/operation of equipment error (CFIT). Any decision error or operation of equipment error that results in a deviation of the aircraft's flight path from a previously established safe route.

- **Unsuccessful ATCo monitoring of terminal area radar (TAR)** (Given a CFTT with TAR available, ATCO fails to detect in time to be able to prevent an imminent CFIT, per CFIT with TAR) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **ATCo failure to resolve conflict in time** (Given a CFTT with ATCO alerted by an MSAW (minimum safe altitude warning) warning, ATCO and flight crew do not correct trajectory in time to prevent an imminent CFIT., per detected CFIT) – can be reduced/increased with

↓**10**% (current traffic with M&S)
↓**10**% (doubled traffic with M&S)
↑**20**% (doubled traffic without M&S)

- **Incorect ATC clearance causes ITC (incorrect trajectory command)** (Given a CFTT with ATCO alerted by an MSAW (Given a manual trajectory command during approach, ITC is executed due to incorrect ATC clearances. This only covers cases where incorrect clearances directly cause the pilot to command flight towards terrain, per flight) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Inadequate trajectories commanded by ATCo** (Given an ATC trajectory command during approach, an ITC is executed due to errors by the ATCO, per flight) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  ↓**10**% (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

- **Inadequate communication with pilot** (Given an ATC trajectory command during approach, an ITC is executed due to inadequate communication between the ATCO and flight crew, per flight) – can be reduced/increased with

  ↓**10**% (current traffic with M&S)
  No change (doubled traffic with M&S)
  ↑**20**% (doubled traffic without M&S)

Appendix H

Total Transmission Time marginal distribution

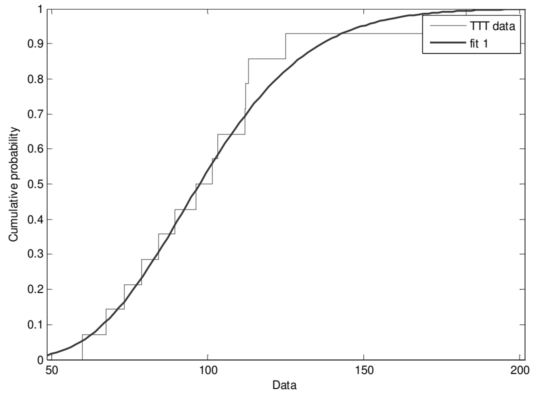
Total Transmission Time (Tot_Trs_Time) is denoted as the total duration (in seconds) of the air/ground communications, per aircraft, for the approach and landing flight phase.

Distribution: Gamma
Log likelihood: -65.9775
Domain: 0 < y < Inf
Mean: 99.9357
Variance: 764.72

Parameter	Estimate	Std. Err.
a	13.0599	4.87442
b	7.65212	2.91158

Estimated covariance of parameter estimates:

	a	b
a	23.76	-13.9216
b	-13.9216	8.4773



Total Transmission Time	$G_{a,b}$(TTT)
59.88	0.0538
67.56	0.1088
73.2	0.1648
78.96	0.2343
84.39	0.3084
89.52	0.3832
96.12	0.4813
101.4	0.5577
103.19	0.5827
111.84	0.6937
112.2	0.6979
113.04	0.7076
125.04	0.8244
182.76	0.994

Source: FAA

Appendix I

Elicitation document for conditional rank correlations between the flight crew and the ATCo error and the Total Transmission Time

Name: ____

In order to connect the Flight Crew Performance model and the ATC performance model, your answer for two additional questions is required. We ask for your cooperation with the remainder that your answers will be confidential.

Question 1. Flight Crew Errors and Total transmission Time

According to the experts' combined opinion in our previous elicitation, of all variables in the model, Weather (mm Rain/hr) had the largest rank correlation with Flight Crew Errors per 100,000 flights. Denote Flight Crew Errors per 100,000 flights as **X**, Weather as **Y**, and Total Transmission Time as **Z**. What is the ratio r_{XZ}/r_{XY}.

- r_{XY}.is positive (the worse the weather is the more errors are likely to happen)
- According to the combined opinion this ratio could be at most 1.8 (in absolute value).
- If you think that no other variable outside the model has an impact on the Flight crew error, and Total Transmission Time "explains all the remaining dependence on flight crew errors" then your answer should be exactly 1.8 (in absolute value).
- If you think that no other variable outside the model has an impact on the Flight crew error but there is still "intrinsic noise" then your answer should be less than 1.8 (in absolute value).
- If you think Total Transmission Time is more important than Weather then the ratio should be larger than 1 but smaller than 1.8
- If you think Total Transmission Time is not as important as Weather then the ratio should be smaller than 1
- If you think Total Transmission Time has no impact on the Flight Crew Errors per 100,000 flights then the ratio should be zero.

Answer:

Question 2. ATC Errors and Total transmission Time

According to the experts' combined opinion in our previous elicitation, of all variables in the model, Man Machine Interface (Using radio only, radio and primary radar, radio, primary and secondary radar and all the previous plus additional tools) had the largest rank correlation with ATC errors per shift. Denote ATC errors per shift as **X**, Man Machine Interface as **Y**, and Total Transmission Time as **Z**. What is the ratio r_{XZ}/r_{XY}.

- r_{XY}.is negative (the less instruments available, the more errors are likely to happen)
- According to the combined opinion this ratio could be at most 4.5 (in absolute value).
- If you think that no other variable outside the model has an impact on the ATC errors per shift, and Total Transmission Time "explains all the remaining dependence on ATC errors" then your answer should be exactly 4.5 (in absolute value).
- If you think that no other variable outside the model has an impact on the ATC errors but there is still "intrinsic noise" then your answer should be less than 4.5 (in absolute value).
- If you think Total Transmission Time is more important than Man Machine Interface then the ratio should be larger than 1 but smaller than 4.5
- If you think Total Transmission Time is not as important as Man Machine Interface then the ratio should be smaller than 1
- If you think Total Transmission Time has no impact on the ATC errors per shift then the ratio should be zero.

Answer:

Appendix J

Dependency measures

1. **Pearson product-moment correlation coefficient** is a common measure of the correlation between two variables X and Y. It reflects the degree of linear relationship between two variables and it ranges from -1 to 1. A correlation of -1 reflects a perfect negative linear relationship between the two variables. A correlation of 1 denotes a perfect positive linear relationship between the variables and a correlation 0 means that there is no linear relationship between the two variables.

2. **Spearman's rank correlation** assesses how well an arbitrary monotonic function could describe the relationship between two variables, without making any assumptions about the frequency distribution of the variable. Hence, it captures any monotonic dependency between any two variables. A rank correlation of -1,1 or 0 has the same interpretation as the product-moment correlation, with respect to the monotonic relationship.

3. **The correlation ratio** is a measure of non-linear relationship between two variables.

Appendix K

Basic aviation concepts

1. **Airspace** means a portion of the atmosphere controlled by a particular country on top its territory and territorial waters. Airspace is divided into two basic types:
   a. **Controlled airspace** – exists where it is deemed necessary that air traffic control has some form of positive executive control over aircraft flying in that airspace
   b. **Uncontrolled airspace** – is the airspace in which air traffic control does not exert any executive authority, although it may act in an advisory manner.

   A country may, by international agreement, assume responsibility for controlling parts of international airspace, such as those over the oceans. For instance, the United States provides air traffic control services over a large part of the Pacific Ocean, though the airspace is international.

2. **Transport category** is a category of airworthiness applicable to large civil airplanes and large civil helicopters. The name transport category is used in the U.S.A., Europe and other countries. Transport category airplanes typically have maximum take off weights greater than 5700 kg, although there is no lower weight limit. Boeing jet airplanes, Airbus airplanes, Learjet 30 series, de Havilland Canada Dash 8, Embraer EMB 120 Brasilia are examples of transport category airplanes. The Convention of International Civil Aviation, throughout its section on Airworthiness of Aircraft, specify the standards that must be met by each civil airplane and civil helicopter used in international aviation. For aircraft, these standards apply if the airplane has a maximum take off weight greater than 5700 kg.

3. The Federal Aviation Regulations (FARs) are rules prescribed by FAA governing all aviation activities in the United States. The FARs are part of Title 14 of the Code of Federal Regulations (CFR). A wide variety of activities are regulated, such as airplane design, typical airline flights, pilot training activities, model aircraft operations and others. The FARs are organized into sections, called parts due to their organization within the CFR. Each part deals with a specific type of activity. For example, 14 CFR part 121 contains rules and operating requirements for scheduled air carrier (commercial aviation). 14 CFR part 135 contains a set of rules and operating requirements for commuter and on demand operations.

4. The Airclaims database provides brief details of all known major operational accidents to jet and turboprop aircraft worldwide. The subset of the Airclaims database purchased by the NLR contains data and descriptive

information about all known airline accidents since 1952. The accident details have been drawn from many sources both official and unofficial, including press reports.

5. **Automatic Dependent Surveillance-Broadcast** (**ADS-B**) is a surveillance technique for air traffic control and related applications. An ADS-B equipped aircraft determines its own position using a global navigation satellite system and periodically broadcasts this position and other relevant information to ground stations and other aircraft with ADS-B in equipment. ADS-B can be used over several datalink technologies and provides accurate information and frequent updates to airspace users and controllers. Hence, it supports improved use of airspace, reduced visibility restrictions, improved surface surveillance and enhanced safety, for example through conflict management.

Under ADS-B, an aircraft periodically broadcasts its own state vector and other information without expectation of an acknowledgement or reply. ADS-B is automatic in the sense that no pilot or controller action is required for the information to be issued. It is dependent surveillance in the sense that the surveillance-type information so obtained depends on the suitable navigation and broadcast capability in the source vehicle. ADS-B is intended to increase safety and efficiency. Safety benefits include improved visual acquisitions and reduced runway incursions of the airport surface. Some of the ADS-B benefits are: (includes Wikipedia site and FAA and adds to references):

- Provides air-to-air surveillance capability
- Provides surveillance to remote areas that do not currently have coverage with radar
- Provides real-time traffic and aeronautical information in the cockpit
- Allows for reduced separation and greater predictability in departure and arrival times
- Enhanced operations in high altitudes airspace for the incremental evolution of “free flight” concept
- Improves ability of air traffic controllers to plan arrivals and departures far in advance.

The use of ADS-B implies a change in air traffic control system, from one that relies on radar technology to a system that uses precise location data from the global satellite network.

6. **EASA** – European Aviation Safety Agency, an agency of the European Union which has been given specific regulatory and executive tasks in the field of aviation safety. EASA became operational on September 28, 2003. The EASA member states are Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia,

Germany, Greece, Finland, France, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, The Netherlands, United Kingdom. An EASA operator is an operator whose home country is an EASA member.

7. **Aircraft generation** represents a distinction among aircraft types based on certification year and applied technology:

- Generation1 – aircraft design and technology pre-1965, for example DC-8, FokkerF27, and Boeing 707.
- Generation2 – aircraft design and technology from the late 60's and 70's, for example Airbus A300, Boeing 727/737-100and -200, DC-9, and DC-10.
- Generation 3 – aircraft design and technology from after 1980, for example Fokker 50/70/100, Airbus A320/330/340 and Boeing 747-400/757/767. These aircraft are designed with modern technology.
- Generation 4 – the most recent types of aircraft.

Appendix L

Nomenclature:

AATT – Advanced Air Transport Technologies
ACSS – Aviation and Communication Surveillance Systems
ADS-B – Automatic Dependent Surveillance – Broadcast
AMSTAR – Airborne Merging and Spacing for Terminal Arrivals
APS – Airborne Precision Spacing
ASAS – Airborne Separation Assurance System
ASR – Air Safety Report
ASTAR – Airborne Spacing for Terminal Areas
ATAAS – Advanced Terminal Area Approach Spacing
ATC – Air Traffic Control
ATSP – Air Traffic Service Provider
ATOL – Air Traffic Operations Laboratory
CDA – Continuous Descent Approach
CDTI – Cockpit Display of Traffic Information
CDU – Control Display Unit
CNS – Communication Navigation Surveillance
CMU – Communication Management Unit
DAG-TM – Distributed Air/Ground Traffic Management
DFW – Dallas Fort-Worth
EICAS – Engine Indicator and Crew Alerting Systems Display
EFIS – Electronic Flight Instrument Systems
FAA – Federal Aviation Administration
FAF – Final Approach Fix
FAS – Final Approach Speed
FMC – Flight Management Computer
FMS – Flight Management System
GPS – Global Positioning System
ILS – Instrument Landing System
LNAV – Lateral navigation
MCDU – Multi-Function Control Display Unit
MCP – Mode Control Panel
ND – Navigation Display
NextGen –Next Generation Air Transportation System
PFD – Primary Flight Display
PDS – Pair Dependent Speed
RNAV – Area Navigation
SMGS – Surface Movement Guidance Control System
STAR – Standard Terminal Arrival Route
STCA – Short Term Conflict Alert
TLX – Task-Load Index
TMX – Traffic Manager Experiment
TRACON – Terminal Radar Approach Control