VILNIUS UNIVERSITY

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MODELING AND VISUALIZATION OF NORM VIOLATION IN DECISION SUPPORT FOR AIRCRAFT APPROACH/DEPARTURE

Doctoral dissertation

Physical sciences, Informatics (09P)

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Scientific supervisor:

doc. dr. Vytautas Čyras (Vilnius University, physical sciences, informatics – 09P)

VILNIAUS UNIVERSITETAS

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NORMINIŲ TAISYKLIŲ PAŽEIDIMO MODELIAVIMO IR VIZUALIZAVIMO TYRIMAS SPRENDIMŲ PARAMAI LĖKTUVO KILIMO IR TŪPIMO FAZĖSE

Daktaro disertacija

Fiziniai mokslai, informatika (09P)

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doc. dr. Vytautas Čyras (Vilniaus universitetas, fiziniai mokslai, informatika – 09P)

Abstract

This dissertation is focused on a method to model and visualize normative rule violation in decision support for aircraft approach/departure. A prototype system is developed to demonstrate feasibility of the proposed method. Norms are taken from the flight rules, maps, approach/departure procedure charts and other legal documents. An example of a normative rule: “Keep 3 degrees descent angle while landing and hold restrictions of the altitude and geography as depicted in the aerodrome chart”. The research is limited to norms applicable in the approach/departure phases of flight. The work is based on the assumption that lidar, which is used together with the radar, provides aircraft position with a high degree of accuracy. This enables the decision support system (DSS) to detect trajectory violations.

A method for norm violation modeling and visualization of normative behavior is proposed. Normative rules are represented as risk item definitions in the DSS. Two norm types are identified: limit-based and deviation-based. Each norm is modeled with a factor (attribute of the trajectory/ies), a normative value, and a predicate. This work proposes a formalization of the violation notion in the context of the DSS. Risk item definition associates a modeled norm with a set of thresholds and discrete risk levels. Risk evaluation maps the observed value to a discrete risk level. Each risk level is mapped to one of traffic light colors, to help guide the air traffic controller decisions. Risk is visualized with a colored indicator on the DSS control panel. Innovative visualization ideas from other projects were adapted for the lidar-based DSS. Hereby, two methods based on 3D views were proposed to visualize the adherence of the aircraft to the airport procedures. Additional objects (projection curtains, wireframe rings) which are integrated into the main 3D window allow the user to visually estimate compliance with the procedure.

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Notation and Acronyms

AIAA	American Institute of Aeronautics and Astronautics
ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance Broadcast
ATC	Air Traffic Control
ATM	Air Traffic Management
ATS	Air Traffic Services
ATZ	Aerodrome Traffic Zone
BZ	Buffer Zone
C2C	Command and Control computer
CAA	Civil Aviation Administration
CD&R	Conflict Detection and Resolution
CFMU	Central Flow Management Unit
CSV	Comma Separated Values
CTT	Common Taxonomy Team
DME	Distance Measurement Equipment
DS	Decision Support
DSS	Decision Support System
EC	European Comission
ENISA	European Network and Information Security Agency
EPZ	Enhanced Procedures Zone
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FL	Flight Level
FP	Framework Programme
GP	glide-path
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
GUI	Graphical User Interface
HALA	HALA! “Towards Higher Automation Levels in ATM” – a SESAR Research Network
IAF	Initial Approach Fix

IAS	indicated airspeed
ICAO	International Civil Aviation Organization
IF	Intermediate Fix
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IS	Information Systems
ISO	International Standardization Organization
IT	Information Technology
lidar	laser radar (LIght Detection And Ranging)
MLS	Microwave Landing System
NDB	Non-Directional Beacon
NM	nautical miles (1 nautical mile equals 1852 meters)
PZ	Protected Zone
RA	Resolution Advisory
RNAV	area navigation (historically – Random NAVigation)
SE	Software Engineering
SESAR	Single European Sky ATM Research program
SID	Standard Instrument Departure
SSR	Secondary Surveillance Radar
STC	Space-Time Cube
TCAS	Traffic Collision Avoidance System
TP	Touchdown Point
VATITA	Italy vACC (virtual area control center)
VFR	Visual Flight Rules
VOR	Very high frequency Omni-directional Radio range
VSM	Vertical Separation Minimum

Introduction

Research Context

The research revolves around a decision support system (DSS) for the air traffic controller. It is a specific application of the decision support systems. The DSS is considered in the context of expanding the air traffic controller awareness in the approach/departure phases by using radar and lidar data fusion and decision support in terms of norm violation risk. Normative rules for aircraft approach/departure are modeled in the DSS in order to estimate norm violation risks for the aircraft. The research proposes the following view to the DSS for the air traffic controller: the DSS performs data fusion, estimates norm violation risks and proposes corrective actions (Fig. 1).

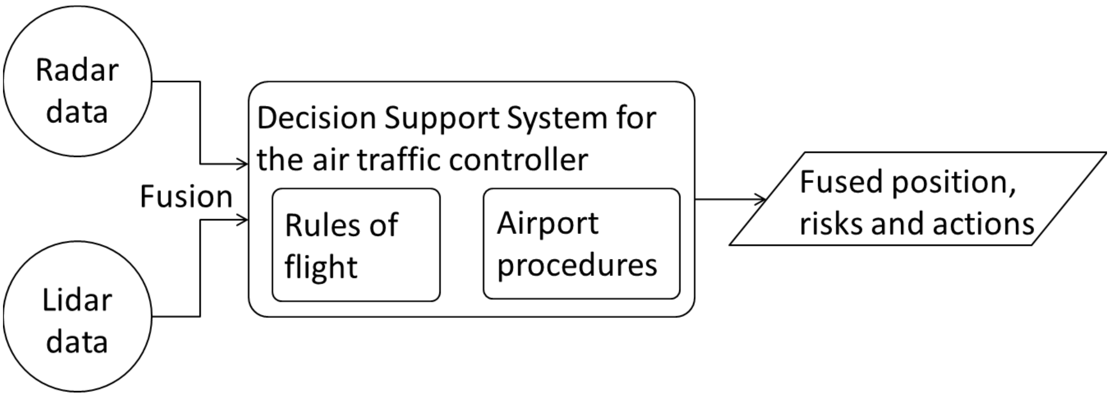

Figure 1. Assumed DSS for air traffic controller

The subject matter of the research is at the intersection of several research areas: decision support in real-time systems, modeling and prediction of aircraft trajectories, specific rules for the aircraft, wake turbulence, aircraft conflict prediction, risk modeling, data fusion, and visualization. Fig. 2 shows areas that are important to the present research.

Statement of the Problem

High level problem addressed in this research is norm modeling and violation risk visualization. The lower level problem is the aircraft approach/departure

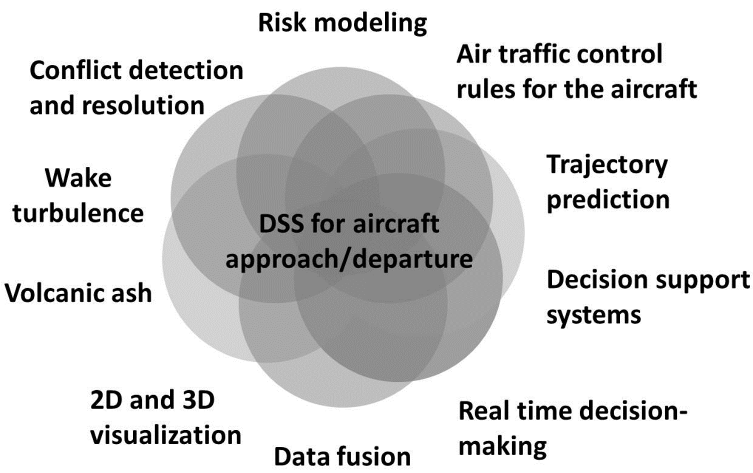

Figure 2. The research areas

norm modeling and violation risk visualization. Visualization is understood as communicating for visual perception (of the human operator). The problem is considered in a new context – the use of lidar (“laser radar”) for aircraft tracking. Lidar gives precise aircraft coordinates; error margin of lidar is measured in meters.

The problem can be classified as norm operationalization problem. Operationalization is the process of developing an operational definition: a list of steps for how to quantitatively measure the complex concept (i.e. to turn the concept into a set of indicators). The research is aimed at a theory (method) which involves the subjects above. The prototype DSS is created with a purpose to demonstrate the proposed theory. Commercial implementations of the DSS are out of scope of the present research.

Motivation

The SKY-Scanner project. This work was inspired by the research performed in the EU FP6 project “Development of an Innovative LIDAR Technology for New Generation ATM Paradigms” (SKY-Scanner[1]), 2007-2010. Participation in the project validated the research problem, and results. Results, which were presented in the project deliverables (Čyras, Dapkūnas, Lapin, Plankis &

[1] Thematic Priority TP1.4 Aeronautics and space, TREN-4-Aero, 037161, http://www.sky-scanner.it/

Savičienė, 2009) and (Čyras, Lapin & Savičienė, 2011) are also reflected in the publications and the text of the dissertation.

The SKY-Scanner project was aimed at developing a lidar-based system to detect and track aircraft up to at least 6 nautical miles (NM) from the aerodrome traffic zone (ATZ) barycentre (Salerno et al., 2008). Lidar (LIght Detection And Ranging) is an optical remote sensing technology that can measure the distance to a target using pulses from a laser. Consequently, a hardware system comprising a rotating laser range-finder and a control computer has been developed as a prototype. The SKY-Scanner software embraces the DSS as a subsystem.

Radar and lidar data fusion. A key presumption is that the decision support is based on lidar and radar data fusion. The lidar is installed in the airport and used in conjunction with the primary radar for aircraft surveillance. The precise aircraft position data from the lidar facilitates detection of risks that are not possible to detect using solely radar data. The present research on modeling norm violation goes beyond the data fusion assumption.

Assumptions. The investigation task rests on the following primary assumptions (see full list of assumptions in section 3.1):

1. Lidar, which is used together with the primary radar, provides aircraft position with a high degree of accuracy (meters). This enables the DSS to detect trajectory violations.
2. The DSS simply informs the controller. Then, a decision on actions is up to him. He can instruct the pilot who is responsible for the safe operation of the aircraft. There is no feedback loop from the pilot to the DSS.

Position of the DSS in the SKY-Scanner system. The DSS is one of the components of the overall SKY-Scanner System (Fig. 3). The DSS receives input data and sends output data to the Command and Control Computer (C2C). The C2C is the central component of the SKY-Scanner system which manages the track data and the communications with other components and the external systems, such as the logistic room of the airport and the ATC/ATM system (SKY-Scanner, 2007). The communications are done asynchronously.

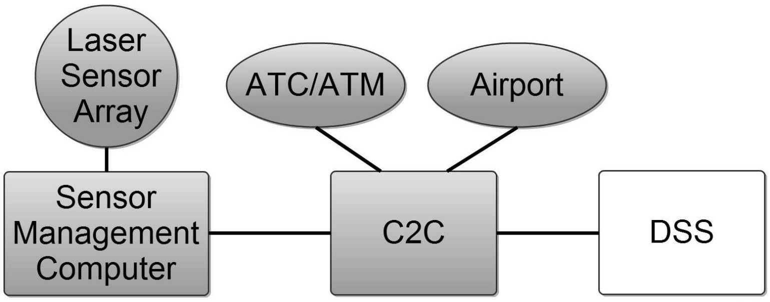

Figure 3. Overview of the SKY-Scanner system (SKY-Scanner, 2007)

The Sensor Management Computer controls the laser sensors and communicates the track data to the C2C in real time mode. The C2C sends to the DSS the track data from the laser sensors and from ATC/ATM radar systems that have a data link with the SKY-Scanner system. Track data is updated periodically, about every second. For each received track data set the DSS sends to the C2C and visualizes on screen the fused position, detected risks and recommended actions.

Research Aims and Objectives

The research aims to develop a method to model normative rules and visualize norm violation risk in decision support for aircraft approach/departure. The research is guided by the assumption that the observed aircraft position is obtained from radar and lidar data fusion.

The following research objectives are stated:

1. Analyze normative rules in aircraft approach/departure domain and identify norms that can be modeled in the decision support system.
2. Analyze existing solutions in aviation decision support, risk modeling and visualization areas.
3. Develop a norm violation risk model for aircraft approach/departure.
4. Develop a visualization model for norm violation: risk visualization and path violation visualization.

5. Develop a prototype decision support system. Model the radar and lidar data fusion, aircraft trajectory prediction, corrective action selection.
6. Demonstrate the proposed method by modeling and visualizing specific norms in the prototype DSS: approach procedures, wake turbulence risk, and ash cloud risk.

Research Approach and Method

Research approach. (Glass et al., 2004) separate research approach and research method. The research approach addresses the general way the research is conducted, whereas the research method addresses the specific methods used. Three research approaches are applied in the computing disciplines: descriptive, evaluative and formulative. The present research is of formulative nature: the research goal is to formulate a method to model and visualize norm violation risk.

Research type and method. Creation of innovative artifacts to solve real-world problems is the central idea of the design (science) research (Hevner & Chatterjee, 2010). The design science research combines a focus on the IT artifact with a high priority on relevance in the application domain. The outputs of design research are constructs, models, methods, theories, algorithms, human-computer interfaces, and other artifacts (Vaishnevi & Kuechler, 2004). Constructive research method (Dodig-Crnkovic, 2010) implies the construction of an artifact (practical, theoretical or both) that solves a domain specific problem, based on the existing knowledge used in novel ways, with possibly adding a few missing links. The construction creates knowledge about how the problem can be solved (or understood, explained or modeled) in principle.

Research method steps. According to (Kasanen et al., 1993), there are six steps in the constructive research method:

1. Find a practically relevant problem which also has research potential.
2. Obtain a general and comprehensive understanding of the topic.

3. Innovate, i.e., construct a solution idea.
4. Demonstrate that the solution works.
5. Examine the scope of applicability of the solution.
6. Show the theoretical connections and the research contribution.

Most of the steps partly overlap (Lindholm, 2008). The steps 2 (obtaining of understanding) and 6 (showing contribution) are done throughout the entire research process. Fig. 4 illustrates how the steps of the constructive research method are also parts of three aggregate phases: the preparatory phase, the fieldwork phase and the theorizing phase.

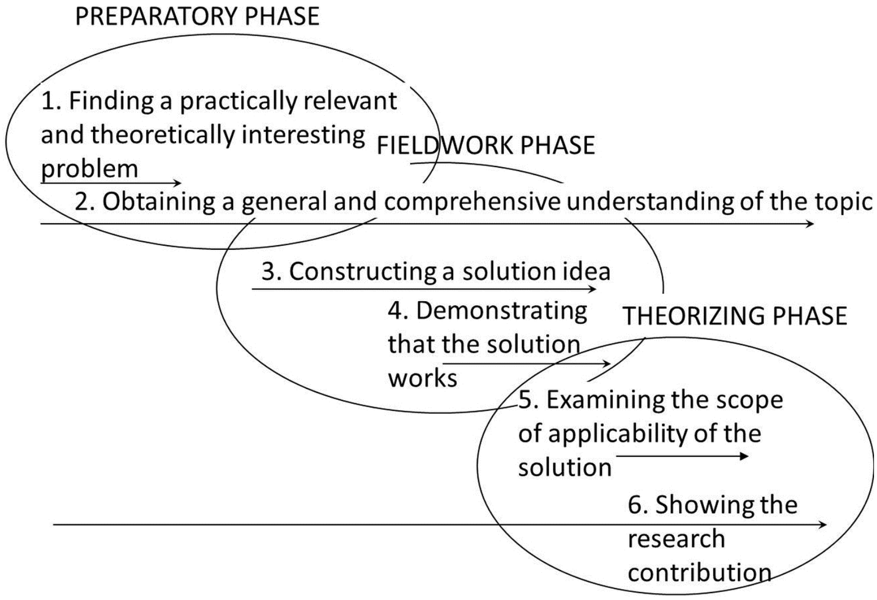

Figure 4. Constructive research method phases and steps, adapted from (Lindholm, 2008)

Research process. The process of the present research has followed a structure of the constructive research method. The study began with extensive analysis of the application domain and existing solutions, although related works had to be analyzed throughout the entire effort. Considerable part was the domain analysis of the air traffic control and the related terminology in order to correctly interpret the normative rules. The research is on the intersection several research areas and the existing solutions were studied in the domains of conflict detection and resolution, risk modeling, data fusion, ATM visualization, and others. Due to space considerations the present dissertation contains only a brief overview of the material. The ideas from the related works were the input for the prototype creation. First throw-away prototypes were vertical prototypes intended to test and refine the core system features – predicting the next position of the aircraft, selecting horizontal maneuver, detecting loss of separation, etc. The study of possible visualizations led to the concept of the current DSS prototype. Individual norms were implemented one after another, concurrently generalizing gathered know-how and defining the conceptual model of norm violation. The early prototypes were tested with artificial data (for instance, assuming the aircraft trajectory is a sinusoid) to demonstrate, that the ideas work in principle. Later, the simulations were performed using a one-day radar data archive from the Naples (it. *Napoli*) Capodichino airport. The prototype was demonstrated to the controllers in the Pescara (a town in southern Italy) airport, the project reviewers, and the controllers in three Lithuanian airports.

Summary of Research Results

1. A method for aircraft approach/departure normative rule modeling and norm violation risk visualization is proposed.
2. Identification of normative rules, that can be modeled in the approach/departure DSS.
3. Norm violation visualization model is proposed. It consists of risk visualization and two path violation visualization models.
4. A prototype decision support system developed. Several specific norms modeled as a demonstration.
5. Participation in the SKY-Scanner project is understood as validation (approbation) of the proposed method.

Contributions of the Dissertation

1. The work is intended as a theoretical research. From the standpoint of computational modeling, a simple model for norm violation risk evaluation and decision making is created. The model is adapted to a particular

application domain; it is based on the specific selection of aircraft approach/departure normative rules.

2. Normative rules in aircraft approach/departure have not been studied on the model level. Existing aviation-related decision support systems typically concentrate on an individual task, and do not distinguish the applied norms from other system elements. Currently, there is no general norm representation framework (norms are represented *ad-hoc*). The research aims to move towards the framework. The perspective introduced in this work explicitly represents a selection of norms in the DSS.

3. The novelty of the work stems from the novelty of the context: the use of lidar for the aircraft tracking. The precise lidar data enables to check adherence of such normative rules, that cannot be checked using only the data from conventional radars.

The present research is relevant both to the research in ATM field, and the current mode of ATC operations in the airports. The research is aligned with the SESAR (Single European Sky ATM Research Programme) research. The DSS could provide support for situation monitoring in the future ATM scenarios. If the constraints on SESAR business trajectories are expressed as risk item definitions in DSS, the trajectory adherence can be monitored by the DSS (see section 5.4). Also, the assumption about human making the final decision accords with the SESAR ATM Target Concept (SESAR, 2007, p. 28).

In the course of the work, a demonstration session was performed with controllers in three airports of Lithuania. Although the main observation was that the precision of current equipment is sufficient for currently applied procedures, some situations where the lidar-based DSS could be used in the current mode of operations were identified[2]:

- when the instrument landing system (ILS) signal is weakened due to rough terrain;

[2] Interviews with controllers from Vilnius, Kaunas and Šiauliai airports in May – June of 2011

- executing ground controlled approach procedure (e.g. for military aircraft not equipped with ILS);
- tracking altitude of targets that have no secondary surveillance radar (SSR) transponders (e.g. gliders), or with broken transponders;

Statements Promoted to Defend

1. A method to model normative rules and visualize norm violation risk in decision support for aircraft approach and departure is proposed.
2. The proposed method enables to represent an identified selection of aircraft approach/departure normative rules.
3. The prototype decision support system demonstrates that the proposed method is possible to implement.
4. Two visualization models for path violation are proposed.
5. The norm violation risk modeling can be automated for the following factors: horizontal and vertical separation, approach/departure procedure vertical profile, indicated airspeed, glide-path and time-based wake turbulence separation. Their modeling was demonstrated in the prototype DSS. For a new factor to be modeled, additional analysis of specifics is needed, as each norm factor is unique.

Approbation

The main results of the dissertation were presented and approved at the following conferences:

1. 14th Conference of Lithuanian Computer Society “Computer Days – 2009”, September 25–26, 2009, Kaunas.
2. 16th Conference on Information and Software Technologies “Information Technologies – 2010”, April 21–23, 2010, Kaunas.
3. 1st Conference on Application and Theory of Automation in Command and Control Systems, ATACC 2011, May 26–27, 2011, Barcelona, Spain.

4. 15th Conference of Lithuanian Computer Society “Computer Days – 2011”, September 22–24, 2011, Klaipeda.
5. 2nd Young Researchers Conference of Lithuanian Academy of Sciences “Interdisciplinary Studies in Physical and Technological Sciences”, February 14, 2012, Vilnius.
6. 10th Baltic Conference on Databases and Information Systems “Baltic DB&IS 2012”, July 8–11, 2012, Vilnius.

Outline of the Dissertation

Chapter 1 presents the normative rules for aircraft approach/departure that are considered in this research. Chapter 2 analyses the related works. Chapter 3 describes the model for norm violation risk estimation. Chapter 4 presents the development of the DSS prototype and path violation visualization. Chapter 5 describes modeling and visualization of specific norms. Chapter 6 presents results, conclusions and open issues.

1 Aircraft Approach/Departure Norms

This chapter presents the normative rules for aircraft approach and departure that are considered in the current research. Section 1.1 introduces normative documents that are the sources of the normative rules for aircraft approach/departure. Section 1.2 is dedicated to the rules of aircraft separation, section 1.3 – separation rules for wake turbulence avoidance, section 1.4 – instrument procedures for aircraft approach and departure, section 1.5 – normative rules, related to ach clouds, section 1.6 – rules applied in collision avoidance systems.

1.1 Sources of Aircraft Approach/Departure Norms

Most of the aircraft in the area where lidar is used for tracking – up to 6 NM from the ATZ barycentre (Salerno et al., 2008) – are either departing or approaching to land, as in some airports the final approach segment may be longer than 6 NM, up to 10 NM (ICAO Doc 8168, 2006, p. 95). In this section, normative rules applicable to the aircraft in the approach and departure phases of flight are reviewed.

Norms in three areas of focus are examined:

1) aircraft trajectories (vertical and horizontal separation, path violation);
2) wake turbulence separation;
3) avoidance of dangerous substances (ash clouds) in the atmosphere.

This research does not discriminate among different modalities of the normative rules (e.g. “allows”, “recommends”, “obligates”, “forbids”). Terms “normative rules”, “legal rules” and “norms” are used as synonyms in the text.

In this research only norms for civil aviation are examined and not military aviation norms (which may be significantly different and not always available to the public). The United Nations Convention on International Civil Aviation (ICAO Doc 7300, 2012) is the basis of civil aviation flight rules. The Convention establishes rules of airspace, aircraft registration and safety, and details the rights of the signatories in relation to air travel. Each state has to ensure that its own rules of the air are as uniform as possible with those established under the convention.

Several documents are examined as the source of normative rules:

- (ICAO Doc 4444, 2007) defines rules for the aircraft separation – for preventing collisions and wake turbulence avoidance.
- Aeronautical charts depict arrival and departure routes and instrument approach procedures. These charts are different for every airport and are designed in accordance with International Civil Aviation Organization (ICAO) requirements and recommendations – (ICAO Annex 4, 2009) and (ICAO Doc 8168, 2006).
- (ICAO Doc 9691, 2007) contains guidance material on volcanic ash, radioactive material and toxic chemical clouds. Only material regarding volcanic ash clouds is examined; besides, the Eurocontrol announcements from summer of 2010 are examined for additional normative requirements regarding ash clouds.

Further, normative rules for aircraft approach/departure found in these documents are presented. Citations from the normative documents are presented in the smaller typeface than the rest of the text.

1.2 Rules for Horizontal and Vertical Aircraft Separation

Two aircraft are considered safely separated if the vertical distance between them is greater than a vertical separation standard or if the horizontal distance between them is greater than a horizontal separation standard (ICAO Doc 9863, 2006). The portion of flight of the aircraft to which the clearance relates may be defined using these terms (ICAO Doc 4444, 2007): taxi (movement of an aircraft on the surface of an aerodrome under its own power, excluding take-off and landing), take-off, departure, en-route, approach, and landing.

Vertical separation minimum (VSM) is regulated as follows (ICAO Doc 4444, 2007):

- Within designated airspace : a nominal 300 m (1000 ft) below flight level (FL) 410, and a nominal 600 m (2000 ft) at or above this level; and
- Within other airspace: a nominal 300 m (1000 ft) below FL 290 and a nominal 600 m (2000 ft) at or above this level.

Lateral separation (separation between aircraft on different routes) must be at 15 NM or more from the navigational facility or track intersection and the tracks must diverge at a certain angle (15, 30 or 45 degrees). For the aircraft on converging tracks, lateral separation exists when at least one of the aircraft is outside the area of conflict. See Fig. 5: the lateral separation points are calculated by the formula $l = S_y/\sin\theta$, where l is the distance of separation point to the intersection, S_y is the lateral separation minima, and θ is the angle between tracks (ICAO Doc 4444, 2007, p. 73).

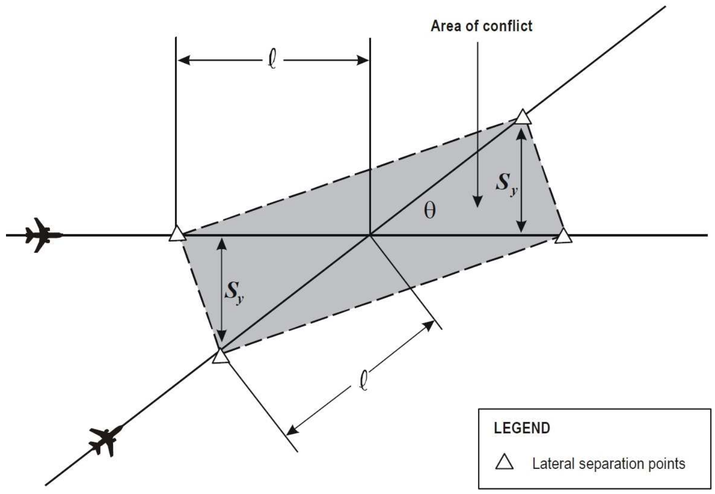

Figure 5. Lateral separation points and the area of conflict (ICAO Doc 4444, 2007)

Longitudinal separation. There are several methods for longitudinal separation:

- Based on time (see example in Fig. 6).

  No two aircraft following the same route must come within 15 minutes flying time of each other. In areas with good navigational aid cover this reduces to 10 minutes; if the preceding aircraft is faster than the following one then this can be reduced further depending on the difference in speed.

- Based on distance using distance measurement equipment (DME)

  For aircraft on the same track, or crossing tracks, separation must be at least 20 NM; if the preceding aircraft is faster than the following one then this can be reduced to 10 NM; for aircraft climbing/descending on the same track separation must be at least 10 NM.

- Based on time with technique of Mach number (a dimensionless number representing the speed of an object moving through air divided by the speed of sound)

  Separation must be at least 10 minutes, or between 9 and 5 minutes, provided that the preceding aircraft is maintaining a Mach number greater than the following aircraft.

- Based on distance using area navigation (RNAV)

  Separation of at least 80 NM must be maintained.

Lateral and longitudinal separation is applied in the en-route phase (ICAO Doc 4444, 2007).

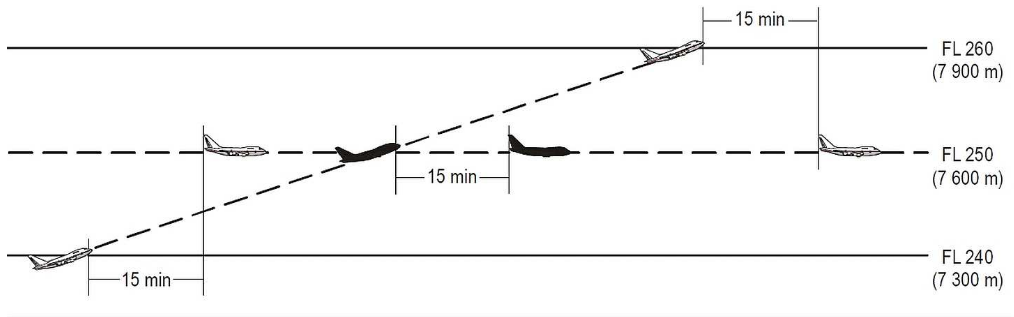

Figure 6. Longitudal separation rule example (aircraft climbing on the same track) (ICAO Doc 4444, 2007)

In the vicinity of the airport the reduced separation minima is used (ICAO Doc 4444, 2007):

- A minimum of 300 m (1000 ft) vertical or a minimum of 5.6 km (3.0 NM) radar separation shall be provided between aircraft during turn-on to ILS localizer courses and/or microwave landing system (MLS) final approach tracks.

- A minimum of 5.6 km (3.0 NM) radar separation shall be provided between aircraft on the same ILS localizer course or MLS final approach track unless increased separation is required due to wake turbulence.
- A minimum of 3.7 km (2.0 NM) radar separation shall be provided between successive aircraft on adjacent ILS localizer courses or MLS final approach tracks (when aircraft are making dependent parallel approach).

Separation of the departing aircraft is time-based (ICAO Doc 4444, 2007):

- One-minute separation if aircraft are to fly on tracks diverging by at least 45 degrees immediately after take-off so that lateral separation is provided.
- Two minutes between take-offs when the preceding aircraft is 74 km/h (40 kt) or more faster than the following aircraft and both aircraft propose to follow the same track.
- Five-minute separation while vertical separation does not exist if a departing aircraft will be flown through the level of a preceding departing aircraft and both aircraft propose to follow the same track.

Separation between departing and arriving aircraft places constraints on the direction which a departing aircraft may take (ICAO Doc 4444, 2007):

- In any direction until an arriving aircraft has started its procedure turn or base turn leading to final approach or, if an arriving aircraft is making a straight-in approach, until five minutes before the arriving aircraft is estimated to be over the instrument runway.
- In a direction, which is different by at least 45 degrees from the reciprocal of the direction of approach, until at least three minutes before the arriving aircraft is estimated to be over the beginning of the instrument runway or before the arriving aircraft making a straight-in approach crosses a designated fix on the approach track.

Separation when holding (ICAO Doc 4444, 2007, p. 101).

When aircraft are being held in flight, the appropriate vertical separation shall continue to be provided between holding aircraft and en-route aircraft while such en-route aircraft are within five minute flying time of the holding area (Fig. 7), unless lateral separation exists.

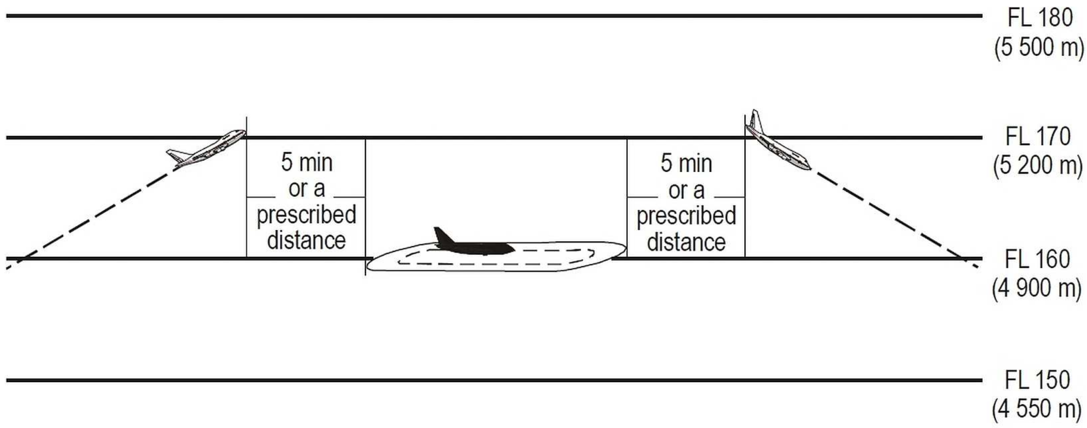

Figure 7. Separation between holding and en-route aircraft (ICAO Doc 4444, 2007)

1.3 Wake Turbulence Separation

All aircraft produce wake turbulence, more correctly called wingtip vortices or wake vortices (CAA of New Zeland, 2008). They are generated from the point when the nose landing gear of an aircraft leaves the ground on take-off and cease to be generated when the nose landing gear touches the ground during landing. Viewed from behind the generating aircraft, the left vortex rotates clockwise and the right vortex rotates counter-clockwise. The greatest hazard from wake turbulence is induced roll (Fig. 8) and yaw. This is especially dangerous during takeoff and landing when there is little altitude for recovery. Aircraft with short wingspans are most affected by wake turbulence.

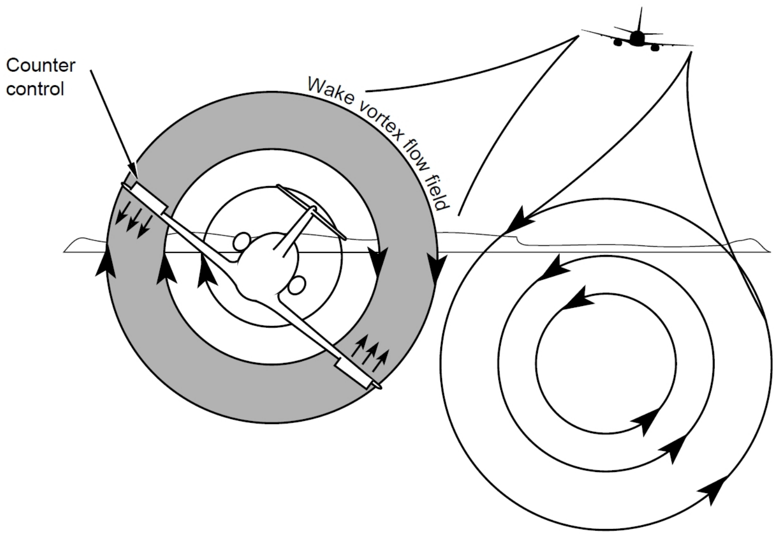

Figure 8. Wake vortex and induced roll (FAA, 1995)

In the flight rules, wake turbulence hazard avoidance is ensured by providing safe separation (Table 1). Wake vortex separation rules are based on aircraft weight categories (ICAO Doc 4444, 2007):

- heavy (H) – all aircraft types of 136 000 kg or more;
- medium (M) – aircraft types less than 136 000 kg but more than 7 000 kg;
- light (L) – aircraft types of 7 000 kg or less;
- super heavy (J) – for Airbus A380-800 with a maximum take-off mass in the order of 560 000 kg.

Table 1. Wake turbulence separation rules (Schonhals et al., 2010)

Weight categories		**Approach**	**Take-off**
Leading aircraft	Following aircraft	Spatial separation (NM)	Time separation (s)
J	J	Not required	Not required
	H	6	120
	M	7	180
	L	8	180
H	H	4	Not required
	M	5	120
	L	6	120
M	L	5	120

Civil aviation authorities also issue recommendations for the pilots, such as keeping above the preceding aircraft's path, or lifting-off before the rotation point of the preceding aircraft (Fig. 9), to help avoid wake vortices.

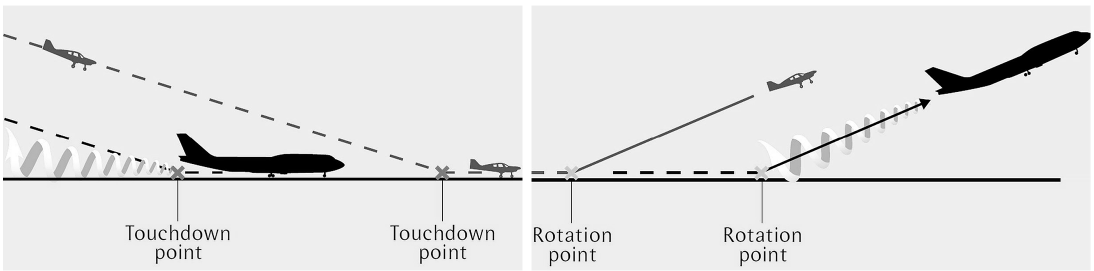

Figure 9. Landing (left) and take-off (right) after larger aircraft (CAA of New Zeland, 2008)

1.4 Instrument Procedures for Approach/Departure

The instrument flight rules (IFR) and instrument procedures are examined as a source for the aircraft trajectory norms, but not visual flight rules (VFR) or visual procedures. The instrument procedures define fine-grained constraints, which can be used to evaluate the observed aircraft trajectories. The visual procedures define only visual reference points for pilots.

The IFR are regulations and procedures for flying aircraft by referring only to the aircraft instrument panel for navigation. Even if nothing can be seen outside the cockpit windows, an IFR-rated pilot can fly, while looking only at the instrument panel. Most scheduled airline flights operate under IFR.

Each airport has its own set of procedures, depending on the terrain, prevailing winds and other factors. For the purposes of the procedures the total flight is divided into the following phases (ICAO Annex 4, 2009):

- Phase 1 – Taxi from aircraft stand to take-off point;
- Phase 2 – Take-off and climb to en-route ATS route structure;
- Phase 3 – En-route ATS route structure;
- Phase 4 – Descend to approach;
- Phase 5 – Approach to land and missed approach;
- Phase 6 – Landing and taxi to aircraft stand.

Approach procedures. Approaches are classified as either precision or non-precision, depending on the accuracy and capabilities of the navigational aids used. Precision approaches utilize both lateral (localizer) and vertical (glide path) information. Non-precision approaches provide lateral course information only.

Instrument approach procedures are depicted in the Instrument Approach Charts (ICAO Annex 4, 2009). These documents graphically depict the specific procedure to be followed by the pilot for a particular type of approach to a given runway. There are different procedures for different navigational aid types – very high frequency omni-directional radio range (VOR), non-directional beacon (NDB), instrument landing system (ILS) and others.

The number of controlled parameters is also different. ILS procedures provide most information about the approach. ILS procedures depict prescribed altitudes and headings to be flown, as well as obstacles, terrain, and potentially conflicting airspace. In addition, they also list missed approach procedures and radio frequencies for communication (Fig. 76, Appendix 1).

An instrument approach may be divided into four approach segments: initial, intermediate, final, and missed approach. Additionally, some routes provide a transition from the en route structure to the IAF (FAA, 2007):

- Arrival: where the pilot navigates to the Initial Approach Fix (IAF), and where holding (keeping an aircraft within a specified airspace while awaiting further clearance) can take place.
- Initial Approach: the phase of flight after the IAF, where the pilot commences the navigation of the aircraft to the Final Approach Fix (FAF), a position aligned with the runway, from where a safe controlled descent back towards the airport can be initiated.
- Intermediate Approach: an additional phase in more complex approaches that may be required to navigate to the FAF. This segment begins at the Intermediate Fix (IF).
- Final Approach: between 4 NM and 12 NM of straight flight descending at a set rate (usually an angle of between 2.5 and 6 degrees).
- Missed Approach: an optional phase; should the required visual reference for landing not have been obtained at the end of the final approach, this allows the pilot to climb the aircraft to a safe altitude and navigate to a position to hold for weather improvement or from where another approach can be commenced.

Departure procedures. Standard instrument departures are depicted in the instrument departure charts (SIDs). The departure procedure contains the significant points defining the departure route, directions to be flown, distances between significant points, altitude and speed restrictions, as well as the description of the departure maneuver in plain text (Fig. 77, Appendix 1). The departure procedure also contains applicable holding patterns and radio frequencies for communication (ICAO Annex 4, 2009, p. 68).

1.5 Ash-cloud Related Rules

Volcanic ash consists of extremely fine particles of pulverized rock (ICAO Doc 9691, 2007). It is comprised predominantly of silica (>50%), which is in the form of glassy silicates. Glassy silicate material is very hard and, when in pulverized form, also extremely abrasive. It can damage the aircraft structures, cockpit windows and engine parts.

Another important property of the volcanic ash is its melting point. As the glassy silicate melting temperature (~1100°C) is below the temperature of jet engines operating at normal thrust (1400°C), volcanic ash can melt and be deposited in the hot section of the jet engine core.

The ability to observe the ash cloud "zone" lateral extent by remote sensing (satellite, ground based lidar, etc.) has greatly improved in recent years (SKYbrary, 2011). However, establishing the detail of ash cloud composition and its vertical extent has proved much more challenging.

The recommendations for the pilots inadvertently entering a volcanic ash cloud (ICAO Doc 9691, 2007), are to (1) immediately reduce thrust to idle (where the engine operating temperature – ~600°C – is below the melting temperature of volcanic ash), and (2) exit volcanic ash cloud as quickly as possible (it may require an immediate, descending 180-degree turn, terrain permitting).

The controllers should follow these procedures, if a volcanic ash cloud is reported or forecast in their region of control (ICAO Doc 9691, 2007):

1) Relay all information available immediately to pilots whose aircraft could be affected to ensure that they are aware of the ash cloud's position and the flight levels affected.

2) Suggest appropriate rerouting to avoid area of known or forecast ash clouds.

3) Remind pilots that volcanic ash clouds are not detected by airborne or air traffic radar systems. The pilot should assume that radar will not give them advanced warning of the location of the ash cloud.

4) If advised by an aircraft that it has entered a volcanic ash cloud and indicates that a distress situation exists:

   - consider the aircraft to be in an emergency situation;
   - do not initiate any climb clearances to turbine-powered aircraft until the aircraft has exited the ash cloud; and
   - do not attempt to provide escape vectors without pilot concurrence.

After the Eyjafjallajökull eruption in 2010, new volcanic ash regulations were issued, and were refined several times by the Eurocontrol, and local civil aviation authorities (Eurocontrol/CFMU, 2010). All these regulations (UK CAA, 2010; Eurocontrol/CFMU, 2010; UK CAA, 2010; ICAO, 2010; EASA, 2010) follow the same pattern:

- The airspace is divided into several zones: a zone where flight operations are forbidden (no-fly zone), a normal flight operation zone, and there may be one or two zones of limited flight operations.
- The division of the airspace into zones is based on the predicted volcanic ash concentration.
- There may be an additional buffer zone (BZ).

See example in Fig. 10 which depicts black, grey and red zones. Black zone is the no-fly zone (ash concentrations above 4×10^{-3}g/m^3). Flights in the grey zone (ash concentrations between 2×10^{-3}g/m^3 and 4×10^{-3}g/m^3) are allowed under certain conditions, provided they are managed by the national ATM provider. Flights in the red zone (ash concentrations between 2×10^{-3}g/m^3 and 2×10^{-4}g/m^3 may be encountered) are allowed provided the aircraft follows the appropriate recommendations of the engine manufacturers.

As the division of the airspace into zones is based on the predicted ash concentration, forecasting ash cloud transport and dispersion is needed. The process of forecasting is based on a combination of a relatively well-understood and modeled meteorological process for forecasting of wind, temperature and stability of the atmosphere. See example outputs from volcanic ash forecast models in Fig. 11.

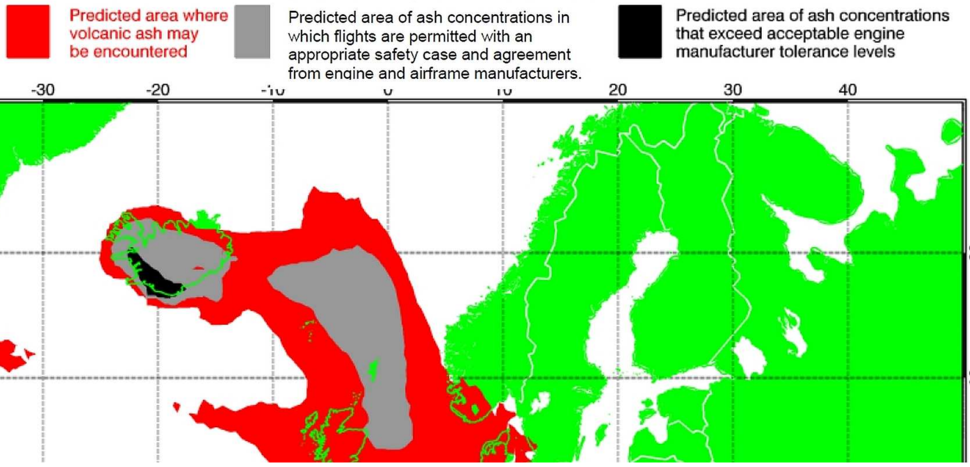

Figure 10. Example chart with enhanced procedures zones (red) and time-limited zones (grey) (UK CAA, 2010)

Recent studies (UK CAA, 2010; Witham et al., 2007) conclude that the current volcanic ash prediction models, although not exact, are sufficient to provide the answers to how the ash clouds propagate.

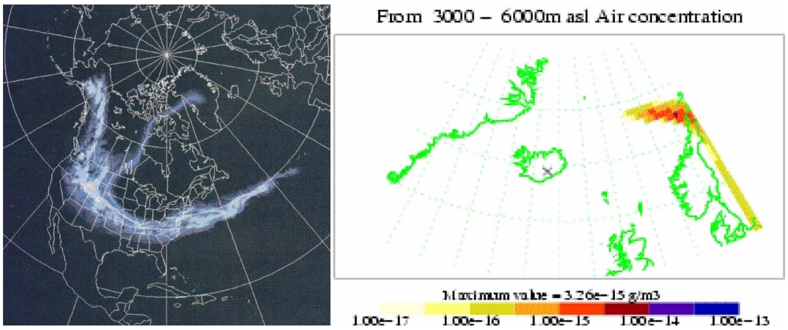

Figure 11. Example screenshots of volcanic ash forecast (ICAO Doc 9691, 2007)

1.6 Norms in Collision Avoidance Decision Support Systems

Collision avoidance systems do not strive to ensure separation but try to avoid collisions (ICAO Doc 9863, 2006). However, they can also be considered from the standpoint of norm representation.

Conflict detection in Airborne Collision Avoidance System (ACAS) depends on two tests (Lee, 2006). A range test is how far a target aircraft is away or how soon this target aircraft will come within a certain time criterion. An altitude test observes how much an altitude of a target aircraft moves toward within a certain altitude criterion. When these two tests pass together, a target aircraft is defined to be an intruder. ACAS thresholds are independent from

ATC separation norms (ICAO Doc 9863, 2006, p. 141). The main ACAS thresholds are time-based, not distance-based like most ATC separation standards. ACAS concept was developed based on a set of assumptions (Williams E., 2004), and the thresholds were defined specifically for this purpose (ICAO Doc 9863, 2006, p. 68).

In contrast, the Next Generation Air Transportation System (NextGen) initiative takes a novel approach to detection and resolution of air traffic conflicts (Chamlou, 2009). The inputs to the detection algorithm are the current position and speed vector of both aircraft and a cylindrical minimum safety protection zone (PZ). The size of the configurable PZ can be assigned values that the Federal Aviation Administration considers as a near mid-air collision incident. That is, a definition of collision (the norm) is represented as a PZ in the system. The choice of PZ allows the algorithm to address a range of applications (from separation assurance to collision avoidance).

1.7 Conclusions

Normative rules for aircraft approach/departure from ICAO flight rule documents can be grouped into these categories:

1. Separation rules:
    - 1.1. Collision avoidance (horizontal and vertical separation minima);
    - 1.2. Turbulence avoidance:
        - 1.2.1. Spatial separation (expressed in distance among aircraft);
        - 1.2.2. Time-based separation (expressed in time intervals that should be kept between taking-off or landing aircraft);
2. Airport charts:
    - 2.1. Procedure tracks (prescribed maneuvers – routes, turns, etc. – that the aircraft should make; deviation from the trajectory prescribed by the airport procedures is called *path violation*);
    - 2.2. Constraints (altitude, speed, and other restrictions);
3. Volcanic ash related restrictions.

This classification covers only the normative rules that were analyzed in this research, but do not cover all available rules. Other norm categories are possible. Other classifications, tailored for other purposes are also possible

Each airport has a different set of approach/departure procedures. Approach/departure procedure constitutes a complex object and contains a number of interrelated norms that define the “ought-to-be” trajectory with additional constraints. Normative rules in the analyzed documents are presented as textual descriptions, graphically (as maps, charts, and schemes), and as tables. This makes identification of the individual norms and modeling of norms a challenge.

The norm operationalization is investigated in the context of expanding surveillance and the ATC control to the approach/departure phases by using radar and lidar data fusion and decision support in terms of norm violation risk. Only norms that can be checked using the lidar-radar fused data (position and speed) will be included in the norm violation risk estimation model.

2 Related Works

This chapter presents the analysis of the related works on the decision support in aviation, real-time decision support systems, visualization, data fusion, risk modeling and wake turbulence modeling. Section 2.1 is dedicated to the characteristics of decision support systems, section 2.2 – conflict detection and resolution (CD&R) process and design factors of CD&R systems, section 2.3 – time-critical decision making models, section 2.4 – methods of visualization of information in air traffic management applications, section 2.5 – data fusion architectures and filtering algorithms, section 2.6 – modeling of risk and decisions on risk, and section 2.7 analyzes wake turbulence modeling methods. Some of the material below describes the context of the present research and could be treated as preliminaries; however, the author treats them as more relevant to the analysis.

2.1 Decision Support Systems

The use of decision support systems is becoming a preferred paradigm in the field of automation in aviation (HALA, 2011). The concept of decision support systems has considerably evolved since it emerged in the 1970s. The definition, taxonomy and the characteristics expected of the present day decision support systems are analyzed below.

2.1.1 Characteristics of Decision Support Systems

Definition. The definitions of what is a decision support system vary depending on the author. Some treat decision support system broadly as a computer-based system that aids the process of decision making. Others specify precise characteristics: interactivity, flexibility, adaptability, data-utilization, ease-to-use, etc. (Turban, 1995). According to (Power, 1997), the term “decision support system” is a useful and inclusive term for many types of information systems that support decision making. He defines decision support systems as interactive computer-based systems intended to help decision-makers utilize data and models in order to identify and solve problems and make decisions. (Arnott & Pervan, 2005) state that decision support systems are a philosophy of information systems development and use and not a technology.

Characteristics. Alter's research, one of the earliest theory developments in this field, identified three major characteristics of the decision support systems (Alter, 1980): (1) they are designed specifically to facilitate decision processes, (2) they should support rather than automate decision making, and (3) they should be able to respond quickly to the changing needs of decision makers. Present day research (Bohanec, 2001) adds the following characteristics: they incorporate both data and models; they are designed to assist managers in semi-structured or unstructured decision making processes; they are aimed at improving the effectiveness – rather than efficiency – of decisions.

Classification. As with the definition, there is also no common taxonomy of the decision support systems. Alter's conceptual-level taxonomy (Table 2) remains relevant (Pearson & Shim, 1994). Subsequent technology innovations have resulted in development of other types of decision support systems (Power, 2001).

Table 2. Decision support system taxonomy evolution

Alter's taxonomy (1980)	**The expanded framework (2001)**
1. File drawer systems	Data-driven decision support systems
2. Data analysis systems	
3. Analysis information systems	
4. Accounting and financial models	Model-driven decision support systems
5. Representational models	
6. Optimization models	
7. Suggestion models	Knowledge-driven decision support systems
	Communications-driven decision support systems
	Document driven decision support systems

Approach/departure DSS as a decision support system. The approach/departure DSS is a *personal decision support system*, according to the classification of (Arnott & Pervan, 2005): it is developed for one decision maker (the air traffic controller), and for one decision task (monitoring of the aircraft conformance to flight rules). The DSS meets the *characteristics*, expected of the modern-day DSS: (1) it covers both data (aircraft position and speed data) and models (norm violation risk model), (2) it is designed to assist the controllers in the decision making process, and (3) it is aimed at improving the effectiveness of the decisions, by applying fine-grained normative constraints and providing better visualizations. It can be classified as *suggestion* (or knowledge-driven) decision support system, which provides suggested decision for a relatively structured task (Power, 2001). The structuring of the task is achieved by creating the risk item definitions.

2.1.2 Level of Automation in Decision Support Systems

The purpose of a decision support system is an attempt to improve the effectiveness of the decision maker (Arnott & Pervan, 2005). It can be improved by automating redundant, manual and monotonous tasks and allowing operators active participation (Cummings, 2004). Therefore, an important characteristic of a decision support system is the level of automation.

It is important to note, that automation can also have an adverse effect on human performance, such as loss of situation awareness, skill degradation and automation bias. The latter occurs when a computer generated solution is accepted as correct and the operator disregards the contradictory information. Full automation is useful in rigid tasks but can cause unanticipated effects in complex tasks. Therefore, in decision support systems design, an important task is the recognition of the human role in computerized tasks and allocation of decision making tasks between humans and computers.

The levels of automation (LOA) range from fully automated to minimal level of automation (Cummings, 2004). A fully automated system (LOA 10) acts autonomously and decides everything. On the contrary, a system with the lowest level of automation (LOA 1) provides no assistance and all decisions and actions are taken by a human.

An air traffic controller's tasks are complex and the events cannot be fully determined in advance. However, an increasing air traffic flow does require raising the operator's work efficiency. High levels of automation are not advisable in systems dealing with dynamic environments with many external and changing constraints (Parasuraman & Wickens, 2008), such as the air traffic control environment. Thus, full automation cannot be taken as an option.

In ATM Target Concept (SESAR, 2007), SESAR defined the role of humans as central in ATM. Humans cannot be eliminated from the decision loop. It means that the choice of automation levels is narrowed to three options, from LOA 2 to LOA 4; in higher automation levels, the system is the central actor, which makes decisions with only some (higher or lower) human intervention.

(Cummings, 2004) examines the effectiveness of computer generated recommendations on a pilot's ability to make decisions in problematic situations. In the studies, pilots were presented with status displays (which merely presented information, LOA 2) and command displays (which recommended action, LOA 4). The conclusions state that unless the decision aids are perfectly reliable, status displays should be used instead of the command displays.

2.2 Conflict Detection and Resolution

One type of decision support tools in aviation are the conflict detection and resolution (CD&R) tools (Kopardekar et al., 2002). Interest in CD&R systems has significantly grown since the Traffic Collision Avoidance System (TCAS) introduction in the early 1990s (Kuchar & Yang, 2000).

Most CD&R works define conflict as an aircraft separation violation (Erzberger et al., 1997; Kelly, 1999; Dowek & Munoz, 2007). However, conflicts with other hazards can be abstracted to the same decision making problem (Kuchar & Yang, 2000). In the case of normative rules explored in this research, the norm violation could be considered a conflict with hazards such as the wake turbulence left by another aircraft, or the boundary of the allowable path in the air. Therefore, the CD&R process structure and design considerations are relevant to the tasks of the present research.

Different aspects of software systems are examined in the context of CD&R and in the context of decision support. Analysis weather specific CD&R systems are decision support systems is out of scope of the present research.

2.2.1 Conflict Detection and Resolution Process

CD&R system definition. Conflict detection and resolution (CD&R) systems: (a) use sensor data to predict conflicts between aircraft, (b) alert humans to a conflict, and (c) possibly assist in the resolution of the conflict situation. The terms “conflict detection” and “conflict resolution” have been adopted to differentiate the alerting and guidance portions (Kelly, 1999).

Terminology. There are differences in the interpretation of the term “conflict” in the research literature. The definition provided by (Kuchar & Yang, 2000) is assumed: “a conflict is an event in which two or more aircraft experience a loss of minimum separation”. Note, that a broadened, more general, definition could also be used, without losing the benefits of the CD&R system characterization.

CD&R phases. The CD&R processes are organized into several phases (Fig. 12). First, the traffic *environment* must be monitored and current *state information* collected. Typically, because of types of sensors used, and sensor errors or limited update rate, the state information carries some uncertainty.

The *dynamic trajectory model* is used to project the states into the future and predict if the conflict is going to occur. Information regarding the current and predicted states is combined to derive *metrics* (e.g. predicted minimum separation) used to make traffic management decisions.

Conflict detection is a process of deciding whether a human should be informed and whether action is needed to maintain traffic separation. In some cases, notification of a conflict is all that is required of the CD&R system. The human operator then determines how to resolve the conflict. When action is considered necessary, the *conflict resolution* phase may be initiated. This involves determining an appropriate course of action and transmitting that information to the operator. Conflict resolution may involve its own state estimates, a resolution maneuver trajectory model, and decision criteria.

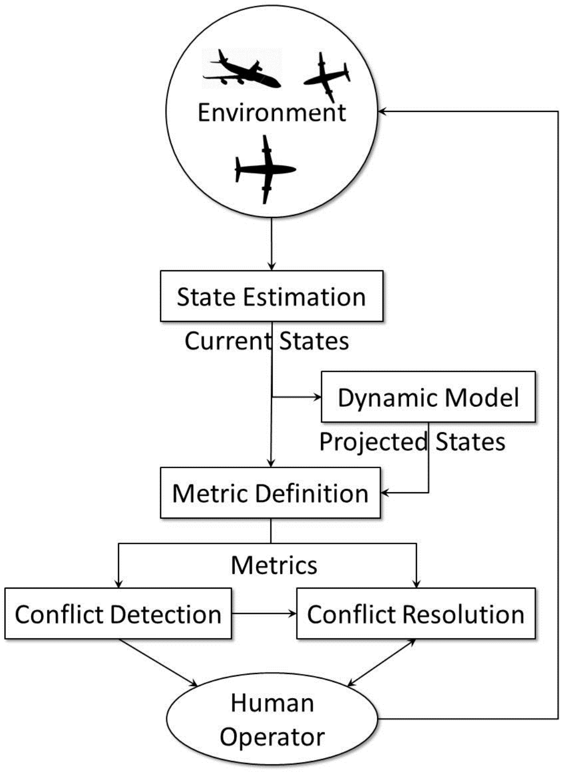

Figure 12. Conflict detection and resolution processes from (Kuchar & Yang, 2000)

2.2.2 Classification of CD&R Modeling Methods

Formal methods. (Dowek & Munoz, 2007) suggest a mathematical framework for the formal specification and analysis of CD&R algorithms. The central concept is the protected zone (imaginary region which defines minimum safe separation distance between aircraft). However, this framework is suitable only for a subclass of CD&R modeling methods. Also, it is tailored to the definition of a conflict as a loss of separation, and it would not be directly applicable to conflicts with other hazards.

CD&R method taxonomy. (Kuchar & Yang, 2000) have made an extensive overview and comparison of the CD&R modeling methods that were available at the time of their study and highlighted the most important design factors of these systems. They suggest a taxonomy covering six design factors:

1) dimensions of state information,
2) method of dynamic state propagation,
3) conflict detection threshold,
4) conflict resolution method,
5) maneuvering dimensions, and
6) management of multiple aircraft conflicts.

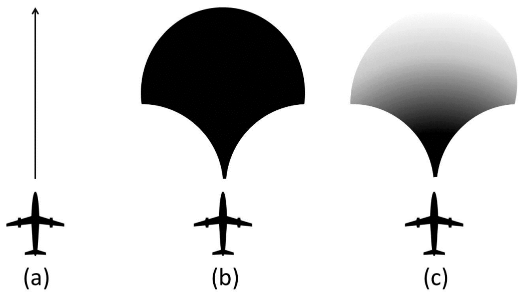

Figure 13. State propagation methods from (Kuchar & Yang, 2000)

The most concrete difference between modeling approaches involves the method by which the current states are projected into the future (*method of dynamic state propagation*). Three fundamental extrapolation methods have been identified (see Fig. 13), termed Nominal (a), Worst-case (b), and Probabilistic (c). In the *Nominal* method, the current states are projected into the future along a single trajectory, without direct consideration of uncertainties. In a *Worst-case* projection, it is assumed that an aircraft will perform any of a range of maneuvers. If any one of these maneuvers could cause a conflict, then a conflict is predicted. In the *Probabilistic* method, uncertainties are modeled to describe potential variations in the future trajectory of the aircraft.

Dimensions of state information show whether the state information used in the model involves purely the horizontal plane, the vertical plane, or both. For example, a ground proximity warning system (GPWS) considers only information on vertical plane.

Conflict detection threshold indicates whether a model explicitly defines when a conflict alert is issued. Models that do not have this explicit threshold may provide valuable, detailed tools and metrics upon which conflict detection decisions can be made, but do not explicitly draw the line between predicted conflict and non-conflict.

Conflict resolution method employed by the model may be of these types: prescribed, optimized, force field, manual or no resolution. *Prescribed* resolution method is fixed during system design based on a set of predefined procedures. *Optimized* method typically combines a kinematic model with a set of cost metrics and searches for trajectories with a lower cost. *Force field* method treats each aircraft as a charged particle and uses modified electrostatic equations to generate resolution maneuvers. *Manual* method allows the user to generate a potential solution and gives feedback as to whether the trial solution is acceptable.

Maneuvering dimensions indicate what dimensions of resolution maneuvers are allowed in the model. Possible maneuver dimensions include turns, vertical maneuvers, and speed changes.

Management of multiple aircraft conflicts describes how the model handles situations with more than two aircraft. This can take two forms: pairwise, in which multiple potential conflicts are resolved sequentially in pairs; and global, in which the entire traffic situation is examined simultaneously.

Considerations. Kuchar & Yang note that it is not always possible to separate conflict detection and conflict resolution. For example, a decision when to take an action might depend on what action is to be taken. This interdependence is one of the factors that make the development of CD&R systems challenging – there are many feasible solutions (Kuchar & Yang, 2000).

This list of design factors is not exhaustive; Kuchar & Yang identify several other important aspects that are not covered by the taxonomy: which current states and metrics are used to make CD&R decisions, how uncertainty is managed in the model, or the degree to which the model assumes coordination between aircraft involved in a conflict. Other factors could also be considered – like the use of intent information (flight plans), distributed vs. centralized architecture, considered time horizon, and others.

Alerting philosophy. (Kuchar, 2001) defined one more design factor. He states that there are three fundamental alerting philosophies: conformance, nominal trajectory, and escape trajectory (Fig. 14).

In a *conformance system* alerts are considered justified when the aircraft does not follow expected behaviour. More formally, a boundary of acceptable operating states is defined beforehand, and an alert is issued when the state of the aircraft exits this boundary.

In the *nominal trajectory philosophy*, the state of the process is projected into the future using some form of trajectory model. The projection is used to determine whether a hazard is explicitly expected to be encountered if the current control strategy continues. Should it become likely that a hazard will be encountered an alert is then issued.

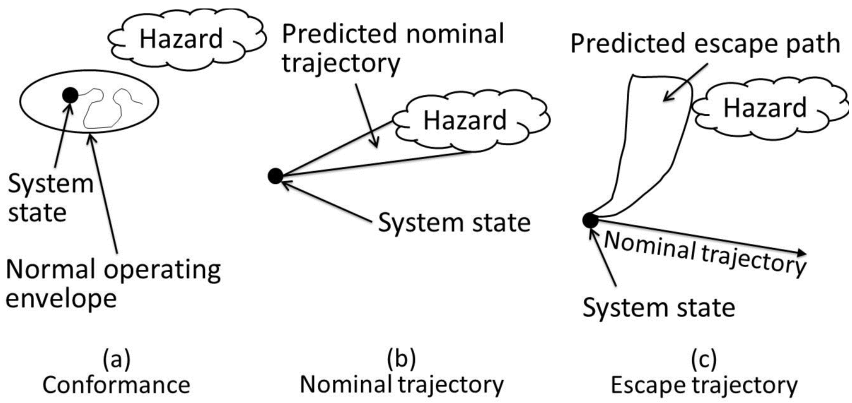

Figure 14. Fundamental alerting philosophies according to (Kuchar, 2001)

The third design approach is to issue an alert when the expected *escape trajectory* is threatened by a hazard. This method extrapolates a trajectory from the current state into the future, but based on the assumption that an alert is issued and corrective action is taken. Conditions for a safe escape need to be defined, and the escape path is examined to determine whether those escape conditions are reachable. If the escape conditions are not reachable at some level of confidence, then an alert is issued.

The nominal trajectory philosophy is better for decision making (with respect to the rate successful alerts versus the rate of unnecessary alerts) than the conformance method, when the trajectories are predictable. When the trajectories are not predictable the conformance system performs better.

2.2.3 Traffic Collision Avoidance System

An example of CD&R system is the Traffic Collision Avoidance System (TCAS)[3]. TCAS is an aircraft system based on Secondary Surveillance Radar (SSR) transponder signals. The system interrogates the transponders of nearby aircraft and from the replies tracks their altitude and range and issues alerts to the pilots, as appropriate. TCAS has the following properties according to (Kuchar & Yang, 2000) classification:

- Method of dynamic state propagation: nominal;
- Dimensions of state information: horizontal and vertical; TCAS uses only range measurements and range-rate estimates to determine if a conflict exists in the horizontal plane.
- Conflict detection: yes; there is a time-based threshold for range, and threshold for altitude, if both are passed together, the target aircraft is declared a threat (Lee, 2006).
- Conflict resolution method: optimized; TCAS searches through a set of potential climb or descent maneuvers and selects the least-aggressive maneuver that still provides adequate protection.
- Maneuvering dimensions: vertical; only climb or descent maneuvers are considered in TCAS II implementations.

[3] Currently, TCAS II version 7.0 is the only commercially available implementation of ICAO standard for ACAS II (Airborne Collision Avoidance System) (Eurocontrol, 2012). The terms TCAS and ACAS are often used interchangeably in the literature, to indicate on-board collision avoidance systems.

- Management of multiple aircraft conflicts: pairwise; if one conflict solution induces a new conflict, the original solution may be modified until a conflict-free solution is found.

2.3 Time-critical Decision Making

Human cognitive processes. Decision making is the process of selecting a choice or course of action from a set of alternatives (Azuma, Daily & Furmanski, 2006). Time-critical decision making strategies rely on the studies of human cognitive processes. Human decision making involves attention and working memory. Attention is how the brain, often consciously though sometimes automatically, selects information for cognitive processing. Working memory refers to the processes used to maintain mental information in a highly accessible state. It is also closely related to what is referred to as the "executive control" (Baddeley, 2007), the conscious ability to switch between effective task sets, contexts, and intentions.

Analogical reasoning. Human decision making processes are facilitated using a variety of different reasoning techniques. One such technique is analogical reasoning (inferring novel solutions via analogy to known solutions/methods). It includes the following serial procedures (Sternberg, 1977):

1. Encoding: translating stimuli to internal (mental) representations.
2. Inference: determining the relationship between problems.
3. Mapping: determining correspondences between new and old items.
4. Application: execution of the decision process.
5. Response: indicating the outcome of the reasoning process.

Significance of the encoding. Since the steps in this reasoning process proceed in a serial manner, temporal ordering and timing of decision support is critical to improving time-critical decision making. Further analyses show that reaction times and error rates increase for more complex encodings. Regardless of the stimuli, the encoding step is the largest single component of the reasoning process, taking ~45% of the overall reasoning time. For example, the encoding of words takes longer than the encoding of schematic pictures, implying that reducing text in displays will facilitate faster decision making.

Decision making philosophies. There are two philosophical approaches toward decision making: the Rational (or logical, analytical) approach vs. the Naturalistic (or action-based, recognition-primed) approach.

The Rational approach assumes a clear set of alternate choices can be generated and their likely outcomes predicted with a significant degree of confidence. It relies heavily on experience or past results to generate the predicted outcomes, and requires that the information the decision is based upon is reliable.

In contrast, the Naturalistic model (Pascual & Henderson, 1997) is based upon imposing an interpretation upon an ambiguous situation. There is an inherent assumption that after a point, too much information can be detrimental. This model assumes that knowledge results from actions, from observing consequences. It does not attempt to come up with an ideal or optimal solution. The Naturalistic model assumes it is not feasible to fully quantify the situation and find a solution mathematically. It may be the best if the present situation is very different from any past situation.

Summarizing, the rational model is objective but requires calculating the utility of each alternative, whereas the naturalistic model highlights the need to provide the human with relevant information.

Time-critical decision making models. Time-critical decision making models are studied mostly in military context: Boyd's OODA loop (Boyd, 1995), the ISAA loop (West, 1996), Headquarters Effectiveness Assessment Tool (HEAT) (Hayes & Wheatley, 2001), the Triage model (Simon, 1977), and the recognition-primed (R-P) model (Klein, 1999). Most of them describe the process of decision making as a serial staged processes that includes steps centered on information gathering, likelihood estimation, deliberation, and decision selection.

OODA loop (Boyd, 1995) is one of the best-known military decision making models. OODA stands for the following steps: Observation (observe the overall situation), Orientation (make judgments of the situation to understand what it means), Decision, and Action (execute and monitor the decision).

The traders' equivalent to the OODA is the **ISAA loop** (West, 1996): Information, Sort by priority, Act, and Assess. One tactic used by the traders with the ISAA loop is to sort trade orders by priority based upon experience, and then first execute market orders with small positions before moving to larger trades. The results of the initial trades either confirm or refute the trader's understanding of the market, allowing the trader to readjust if the market does not respond as anticipated (a naturalistic strategy.)

Six steps of the **HEAT** are (Hayes & Wheatley, 2001): monitor, understand, develop alternatives, predict, decide, and direct. The first two steps are to collect the facts and produce an understanding of the situation, while the last two steps are those, in which commanders make decisions and disseminate them to forces for execution. Decision making encompasses the middle four steps. This model explicitly points out that the commanders commonly skip the middle two steps (develop and predict).

(Simon, 1977) models the decision making process in three high-level stages (called **Triage model** (Azuma, Daily & Furmanski, 2006)): (1) Intelligence: fact-finding, problem and opportunity sensing, exploration; (2) Design: formulation of solutions and generation of alternatives; and (3) Choice: decision making, goal maximization, and implementation.

(Klein, 1999) described the **R-P model**. This model assumes experience is the primary source of wisdom in decision making, and results from observations and studies of real-life case, rather than in laboratory conditions. It generally applies to crisis situations where time is very limited. This process does not compare solutions against each other, but solutions against the situation in a serial fashion. Its goal is a "good enough" solution, not the ideal one. This approach allows saving decision making time that is needed for reasoning. R-P model is valuable when compared situations are not far from each other. If decision is complex or depends form multiple arguments, quick decision is not possible (Azuma, Daily & Furmanski, 2006).

Comparison of models. Many of the models share common aspects and attributes but differ in the order of steps, area of emphasis or underlying assumptions. Significant aspects of the models are:

- limited of ample time for decision making,
- decision optimization level,
- the level of efforts to analyze decision outcomes,
- how experience is involved to decision making.

Decisions are required in either simple or complex situations. Simple situation requires one quick decision and corrections are not needed. For complex situations usually it is important to find an optimal decision in a certain time. Table 3 summarizes significant aspects of the reviewed models.

Table 3. Comparison of decision making methods

Method	**Time for decision making**	**Decision optimization level**	**Efforts to perform decision**	**Cumulated experience**
OODA loop	Medium	Low	Medium	Involved in situation assessment
ISAA loop	Small	High	High	Prioritization of available solutions
HEAT	High	High	High	Involved in developing alternatives
Triage	Large	High	High	Involved in problem analysis
R-P	Small	High	Small	Formal rules and procedures

Considerations with respect to approach/departure DSS. Simple decisions are taken during landing or take-off, for example, turn left or right. There is no space for trial and error. Optimization level is important as corrections are not possible. Approach/departure procedures are based on strict rules. Presenting the aircraft actual position with respect to a visualized approach/departure procedure enables controllers to visually follow the situation and to estimate whether aircraft adheres the assigned procedure.

2.4 Visualization in ATM Systems

2D radar displays. Constantly rising air traffic requires more information to display on the controller's screen. Current ATC workstations have 2D radar displays. Such display combines graphical and symbolic information. The geographical aircraft position is shown on 2D plan while the third dimension (altitude) and speed is presented by symbols (Fig. 15). In order to follow the actual situation and to indicate possible future troubles, the controller performs mental calculations of the altitude and speed.

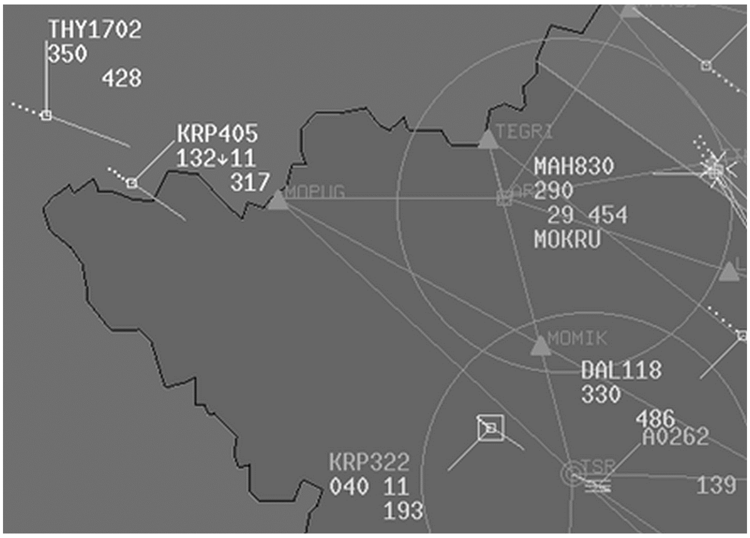

Figure 15. Screenshot of the radar display (Hoober, 2008)

3D displays. Several 3D visualizations have been built for ATC applications as research systems, other projects explore how to integrate the fourth – time – dimension (Azuma, Neely, Daily & Geiss, 2000). Novel 3D visualizations (Fig. 16) enable presenting altitude as the third dimension and reducing the amount of symbolic information. A 3D view requires less cognitive effort to interpret altitude information. It supports more informed decision making on the vertical dimension (Wong et al., 2007). However, it is easy to clutter 3D view with unimportant details aiming to render a realistic landscapes. 3D interfaces should be minimalistic and abstract from details (Rozzi et al., 2007).

The 3D displays have several disadvantages, including hampered distance estimation due to perspective distortion, no possibility to oversee global traffic out of the camera view, difficulty to locate traffic at the far end of the scene and difficult navigation/selection (Rozzi et al., 2007).

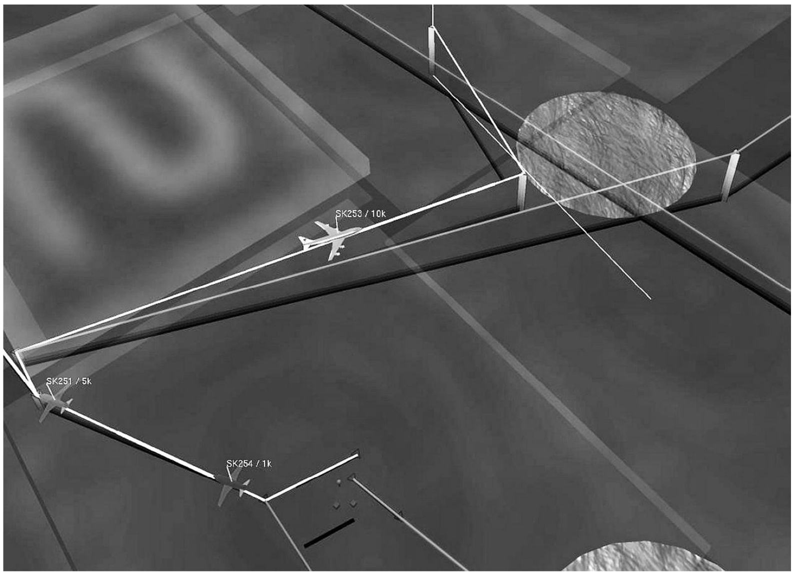

Figure 16. Screenshot of experimental 3D ATC display (Bourgois et al., 2005)

Multi-view displays. One of the methods to show both horizontal and vertical perspectives without distortions is to use the multi-view displays, which show top-view and side-view projections side by side. Such approach was used in the earliest DSS prototypes (Fig. 17). However, such multiple view configurations require the user to scan information across different sources, which brings a perceptual cost (Rozzi et al., 2007). The real-time demand imposed on the air traffic controllers does not allow for such time-consuming data exploration.

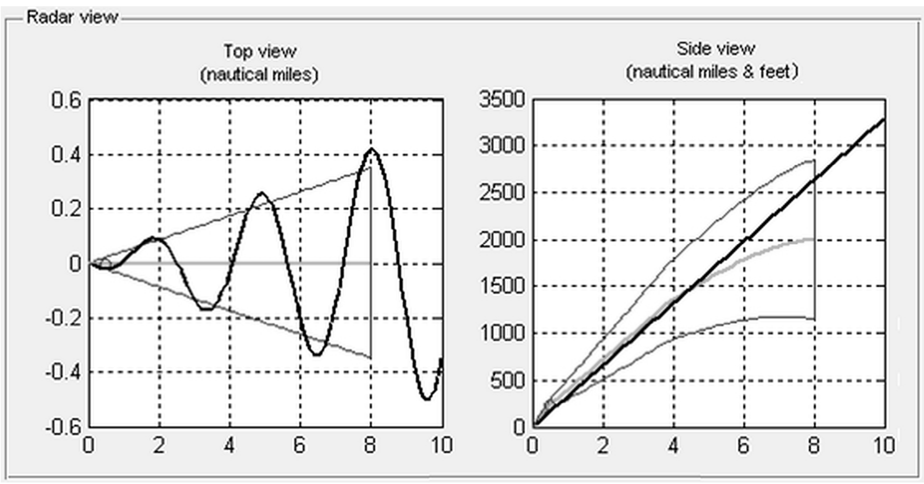

Figure 17. Multi-view interface from the early DSS prototype

Visualization considerations for the approach/departure DSS. In the current research, it is proposed to visualize the altitude dimension in 3D in the approach/departure DSS. This would reduce the cognitive workload as the controller will monitor rather than interpret alphanumerical characters and hold them in his mind. In order to overcome the drawbacks of the 3D displays, existing visualizations in aeronautics and geographical domains are analyzed for possible strategies. Visualizations from the following sources are analyzed:

- Space-time cube representations
- Strict 3D visualization of air traffic concepts developed for free flight in Hughes Research Laboratories.
- Visualizations from the project "3D-in-2D Planar Displays for ATC".

Space-time cube. Space-time cube (STC) is a structure that is used to depict target activities in space-time context (Gatalsky, Andrienko & Andrienko, 2004; MacEachren, 2004). The horizontal axes record the position and location changes of objects. The vertical axis provides an ordered and synchronized sequence of events. In its basic appearance these images consist of a cube with geography on its base, while the cube's height represents time (Fig. 18). A typical STC contains object trajectories, also known as space time-paths, of an object moving in time. It is a proper choice representing a relationship between the horizontal position, time and speed.

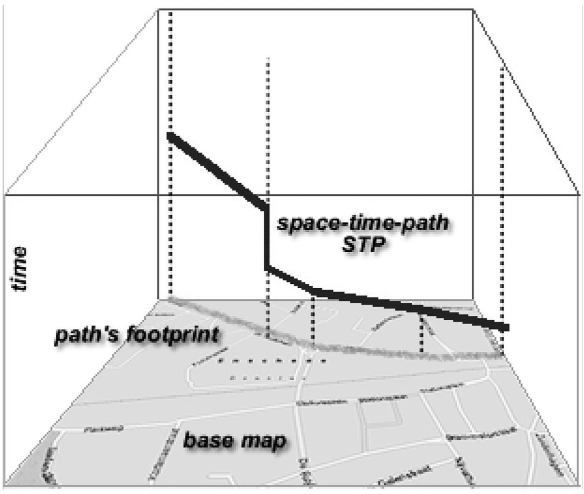

Figure 18. The STC basics, vertical segment represents time spent at the same location (Kraak, 2003).

According to this technique, airport plan is on the bottom of the cube, aircraft horizontal positions are shown by points in three-dimensional space with the vertical dimension corresponding to time. Apart from the trajectories, STC display helps to explore speed: sloping segments indicate fast movement, while steep segments correspond to slow motion. STC represents a relationship between the horizontal position, time and speed, whereas the approach/departure DSS needs to visualize the relationship between track, distance and altitude. Therefore, STC is not a suitable visualization choice.

Strict 3D view. A strict 3D was used to detect conflicts in the terminal area of Boston Logan Airport (Azuma, Daily & Krozel, 1996); see Fig. 19. 3D perspective display shows the situation in a top-down plan-view. The view can be exocentric, looking at the entire situation from a remote perspective, or egocentric, following an individual aircraft to see the pilot's perspective.

Aircraft mode represents a set of linked wireframe rings in space, they draw a tunnel in the sky that aircraft appears to fly towards.

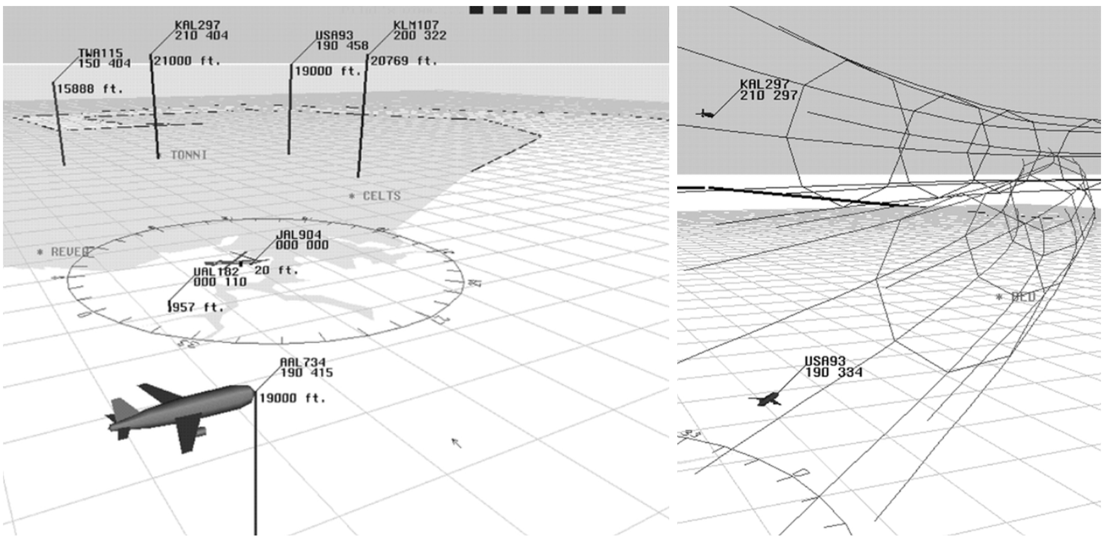

Figure 19. Strict 3D view screenshots (Azuma, Daily & Krozel, 1996)

This method can be adapted to visualize a relationship between horizontal position, distance and altitude. The tunnel can represent a trajectory prescribed in an assigned instrument approach procedure. The violation is detected when the aircraft is located outside the rings.

2D-in-3D visualizations. Combined visualizations enable to show contextual and altitude information at the same time. The following strategies are proposed in the 2D and 3D integration method (Rozzi et al., 2007):

- select a portion of the main 2D view and represent it in 3D;
- show 2D projections (walls) in the 3D display with the projections of the aircraft.

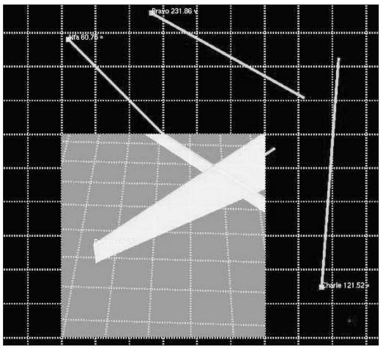

Figure 20. Screenshot of “picture within picture” (Rozzi et al., 2007)

The first strategy enhances a part of the main 2D view by representing it in 3D. Though Fig. 20 depicts a visualization of the en-route phase, it can be also adapted for approach and departure.

Visualizations with 2D walls in the 3D display provide controllers with data needed to assess the traffic situation or guide aircraft accurately (Wong et al., 2007). The walls could be used to track the holding stack, or observe the conformance to the approach procedure (Fig. 21).

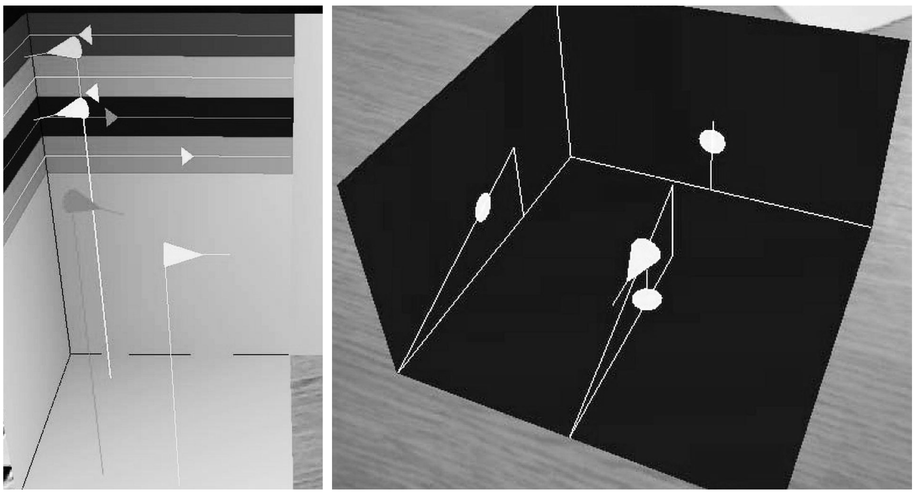

Figure 21. Screenshots of 2D-in3D views (Wong et al., 2007)

The latter scenario requires a precise aircraft position that cannot be achieved with the sole radar equipment. Current surveillance technologies cannot implement those visualizations because of inaccuracy of radar devices. The lidar provides the exact aircraft position for the approach/departure DSS. Therefore this visualization can be implemented.

The proposed approaches offer two combination types: 3D within 2D and vice versa. Though the first strategy is universal and presents the needed data, the latter (2D in 3D) is more intuitive. Hence, this method is better suited for approach/departure DSS.

Controller needs in ATM visualization. The focus is on what visualization aspects are important to the controller, because different ATM system users (e.g. pilots) might have entirely different visualization needs. To find out the possible shortcomings of the existing visualizations, accident analysis reports (van Es, 2003) of the National Aerospace Laboratory (NLR) were examined. The report on accidents which occurred in 1980-2001 concludes that 12.7% accidents occurred in take-off and landing phases. Take-off accidents comprise 6.1% of overall accident amount and landing – 6.6%. The analysts of the ATM related accidents arrived at the conclusion that the causal factors were low visibility and incorrect or inadequate instruction/advice given by ATC. A frequent event factor in landing accidents was non-adherence to procedures by flight crew. Thus, there is a need for improved *situational awareness* and *recognition of the flight crew adherence* to the assigned procedures.

2.5 Data Fusion

Data fusion definition. Data fusion is defined as theory, techniques and tools used for combining sensor data, or data derived from sensory data, into a common representational format that is appropriate for deriving decisions (Bosse et al., 2006; Mitchell, 2007). Data fusion systems use different techniques: digital signal processing, statistical estimation, control theory, artificial intelligence, classic numerical methods, etc. (Hall & Llinas, 1997).

Target tracking. Data fusion is important in aviation target tracking. The purpose of tracking is to collect sensory data from the surveillance volume containing one or more potential targets of interest and then partition the sensory data into sets of observations measured from the same target (Gad et al., 2004). Using multi-sensor systems in this case has the advantages over single sensor systems. Multiple sensors make it possible to obtain multiple viewpoints, reduce the ambiguity and obtain a more precise estimate of object kinematics. The sensors used for the tracking are not necessarily different, e.g. there is experience in multi-radar data fusion (Rodriguez et al., 1997).

Fusion architectures. There are three principle fusion architectures (Mitchell, 2007): centralized, hierarchical, and distributed (Fig. 22). In a *centralized* architecture, there is a single node that performs alignment, association and updating of tracks. In the *hierarchical* architectures, the fusion nodes are arranged in a hierarchy with the higher level nodes processing results from the lower level nodes and possibly providing some feedback. In a *distributed* architecture, there is no pre-determined superior/subordinate relationship, each node can communicate with any other node subject to connectivity constraints, and the communication can be asynchronous.

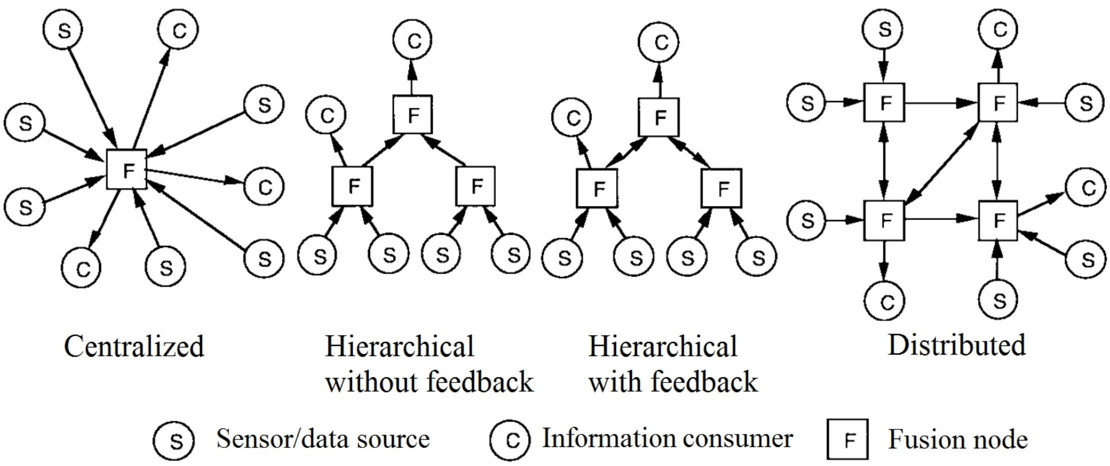

Figure 22. Data fusion architectures according to (Liggins et al., 1997)

Fusion steps. The fusion process for target tracking is composed of three steps between time scans: alignment, association, and updating (Gad et al., 2004). *Alignment* converts the data of each sensor to a common coordinate system and extrapolates the tracks to the same time as the measurements. *Association* partitions the measurements into sets that could have originated from the same targets. *Updating* (filtering) step renews estimated positions of each target with sensor measurements.

Filtering algorithms. The heart of data fusion process is filtering. Several filters, often used in tracking systems are: Kalman filter, alpha-beta filter, Wiener filter, and particle filter. The first three are recursive fading memory filters. All filters estimate a process by using a form of feedback control: the filter estimates the process state at some time and then obtains feedback in the form of (noisy) measurements. Equations for the filters fall into two groups: *time update* equations and *measurement update* equations. The time update equations are responsible for projecting forward (in time) the current state, the measurement update equations are responsible for the feedback. Of the first three filters, Kalman filter is considered to be most accurate, but most costly to implement (Singer & Behnke, 1971). Recent studies suggest, that particle filters can achieve improvement in performance (Gustafsson et al., 2002) or smaller errors (Kambhampati et al., 2004) compared to existing Kalman filter based solutions. However, (Blanc et al., 2005) state that in target tracking applications the computation time of the Kalman filter is much better than that of the particle filter. Computation time is the key factor in the DSS as the fusion and risk evaluation has to be done every second.

Kalman filter. A Kalman (Zarchan & Musoff, 2005) filter combines measurement data, plus prior knowledge about the system and measuring devices, to produce the estimate of the system state in a way that minimizes the mean of the squared error (Mayeck, 1979). In each step the filter updates error covariance estimates. Kalman filter is based on the assumption that the system can be described through a linear model, and the system and measurement noises are Gaussian. For non-linear systems Kalman filter extensions – the extended Kalman filter, the unscented Kalman filter (Duan et al., 2005), etc. – were defined. Since the early sixties the Kalman filter and its variants have emerged as the preferred filters for tracking applications (Mehrotra & Mahapatra, 1997).

One of the disadvantages of Kalman filter is that it is necessary to have previous knowledge about the system and measuring devices, i.e. the initial conditions of the mean and variance state vector (Jalles, 2009). Another disadvantage is that the assumptions of linearity and Gaussianity of the Kalman filter cannot manage complex scenarios (Bazzani et al., 2009).

Alpha-beta filter. The α-β filter, which assumes a constant-velocity trajectory, is similar to the Kalman filter, except that the gain coefficients are not adaptively changed (Bhagavan & Polge, 1974). The simplification is based mainly on the elimination of coordinate interaction terms in the covariance expressions, on the reduction in the size of the state and measurement vectors, and on the adoption of simple equations of motion (Tilley et al., 1985). While the filter has an excellent performance for tracking non-maneuvering vehicles, it has little capability to track severely maneuvering vehicles. However, because of its extreme simplicity, it is often considered as a candidate for a tracking filter (Singer & Behnke, 1971). The α-β filter is used in TCAS systems for range and altitude (ICAO Doc 9863, 2006, p. 29).

Wiener filter is a linear filter under the stable condition based on the least mean square error criteria. The gain vector of the filter is calculated off-line, thus it requires no auxiliary equations. This filter can track both maneuvering and non-maneuvering vehicles well (Singer & Behnke, 1971). However, it was intended to a very restricted class of filtering problems: separating one noise-like signal from another, which is correlated to the first in some known way (Øien & Ramstad, 2001). Therefore the results of Wiener filtering should be viewed with a degree of caution (Brown & Hwang, 1997).

Particle filter. Particle filtering is a sequential Monte Carlo technique that recursively computes the posterior probability density function (Kambhampati et al., 2004). Multiple copies (particles) of the variable of interest are used, each associated with a weight that signifies the quality of that specific particle (Rekleitis, 2004). After each action, each particle is modified accordingly to the existing model, including the addition of random noise. Then, each particle's weight is re-evaluated based on the latest sensory information available. At times the particles with small weights are eliminated, a process called resampling.

2.6 Risk Modeling

Risk components. ISO 31000 standard defines risk as a combination of the probability of an event and its consequence (ISO, 2009). The term "probability" may be replaced by more gentle term "likelihood" (Mahler, 2009). This is a usual approach in managerial disciplines. In other contexts, the definition of risk may be one-dimensional, for example, based only on probability (Boyle, 1999), or other criteria, e.g. radiation dose in (Bender, 2011). Both components of risk may be described either qualitatively, or quantitatively. Once a risk is identified, it can be analyzed in order to estimate the risk level by combining the estimated probability and the consequences (Mahler, 2009), see Fig. 23.

RISK MATRIX		CONSEQUENCES				
		Insignificant	Minor	Moderate	Major	Catastrophic
LIKELIHOOD	Very likely	Medium	High	High	Very high	Very high
	Likely	Medium	Medium	High	High	Very high
	Possible	Low	Medium	Medium	High	High
	Unlikely	Low	Low	Medium	Medium	High
	Rare	Low	Low	Low	Medium	High

Figure 23. Estimating risk level according to (Mahler, 2009)

Decision on risk. During risk evaluation decisions have to be made concerning which risks need treatment and which do not, as well as concerning on the treatment priorities. The decisions made are usually based on the level of risk but may also be related to thresholds specified in terms of consequences, likelihood and other criteria (ENISA, 2006). The well-known traffic light model (Fig. 24) is often used in determining tolerability of the risk (Boyle, 1999; Bender, 2011; Renn & Graham, 2005). Red risk level usually signifies intolerable risk, the yellow one indicates tolerable risk in need of further actions, and the green risk level shows acceptable or even negligible risk.

Hazard identified	Traffic light rating
1. The river was chest deep on the shorter group members.	Yellow
2. The current was flowing quickly making it difficult to hold one's footing.	Yellow
3. The water was icy cold but the air temperature was warm.	Green
4. A submerged tree branch could be seen piercing the surface downstreem.	Red
5. It was late and several group members were in a hurry to get home.	Yellow

Figure 24. The traffic light decision making model example (Boyle, 1999)

Risk modeling. Risk modeling is about modeling and quantification of risk, it provides insight into the relationships between scenarios, likelihood and consequences (Haimes, 2009). Model simplifies real processes by aggregating numerous circumstances into a few, broad categories. One way to classify mathematical models is linear versus nonlinear. A linear model is represented by linear equations: i.e. all constraints and the objective functions are linear.

Linear risk model. (Jewel, 1961) defines a linear risk model with a threshold (Fig. 25). The decision variable z is measured in the same units as the random parameter x, and the risk function $R(z, x)$ is assumed to be piecewise linear in two parts, depending upon whether or not x is less than z. Furthermore, the initial ordinate $A(z)$ and the discontinuity $D(z)$, are assumed to be functions of the decision variable, while the slopes ($m1$ and $m2$) are not.

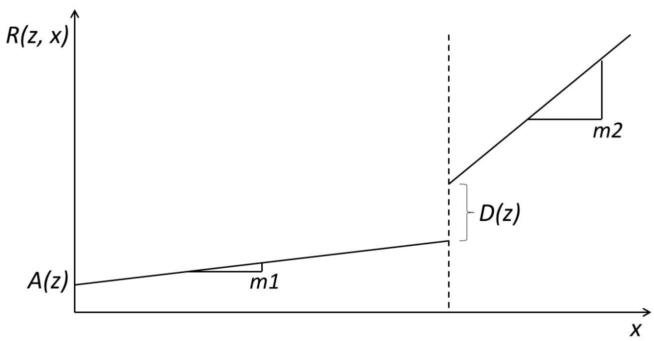

Figure 25. Linear risk function according to (Jewel, 1961)

Piecewise linear risk models are used in financial domain, as approximations of quadratic forms (Mitra, 2003; Kono & Yamazaki, 1991; Kono, 1990), and in medicine (Gandomi & Jandaghi, 2012). In medicine, linear risk model is called the threshold model, as opposed to linear non-threshold model (Williams et al., 2008; Appleyard et al., 2005; Kraemer et al., 2001).

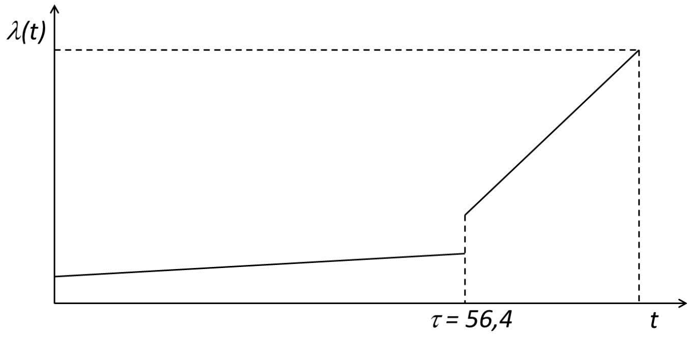

Figure 26. Piecewise linear risk example, *t* – time, *λ(t)* – risk (Gandomi & Jandaghi, 2012)

2.7 Wake Turbulence Modeling

Wake turbulence parameters. Wake turbulence is a complex phenomenon (Larsen et al., 2007). It depends on many atmospheric parameters such as wind, temperature, pressure, etc. It also depends on aircraft weight and wing length, speed, position in the air. However, as the aircraft weight is a basic factor, the vortex strength increases proportionally. The greatest strength occurs when the generating aircraft is heavy, at slow speed with a clean wing configuration (FAA, 1995).

Vortex movement and lifespan. Vortices usually persist for between one and three minutes, with survival often greatest at low level in calm or very light wind conditions and at higher altitudes in thinner air. On approach and takeoff, the wake descends until it reaches the ground and move laterally. With no crosswind, the two vortices move apart to clear the flight path. Crosswinds can cause vortices to move (Fig. 27). A light, quartering tailwind requires maximum caution.

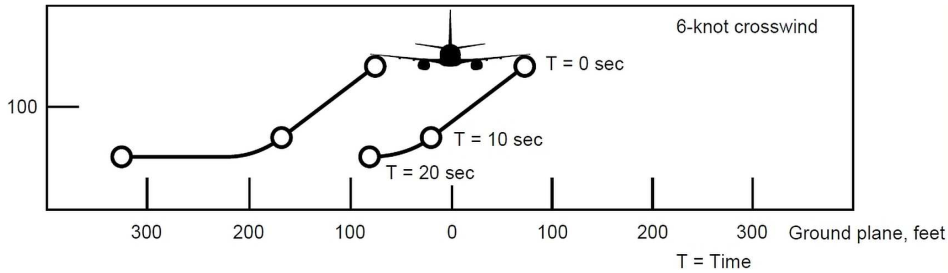

Figure 27. Wake vortex horizontal motion, greater crosswind (FAA, 1995)

Table 4 summarizes characteristics of the wake vortices (CAA of New Zeland, 2008; SKYbrary, 2012; FAA, 1995; Airbus Customer Services, 2005).

Table 4. Wake turbulence characteristics

Vertical movement	
Descend rate	300-500 feet per minute
Stabilization	500-900 feet below the origin
Stop of the downward descend	½ wingspan (up to 50-100 feet) of the ground
Horizontal movement	
Mov. Speed (no wind)	2-3 knots
Mov. Distance	Up to 1500 feet
Mov. In no crosswind (0 knots)	Move apart to clear the flight path
Mov. In light crosswind (1-5 knots)	One vortex remains near the flight path
Mov. In greater crosswind (> 5 knots)	Move quickly across the flight path and break up
Lifespan	
Still air	Up to 100 seconds
Wind speed 1-5 knots	Up to 85 seconds
Wind speed 5-10 knots	30 seconds

Wake vortex modeling. Due to the stochastic nature of turbulence, the development costs of exact model are extremely high, thus almost all models have a certain degree of inaccuracy. First wake vortex models assumed several effects that impact wake vortices, such as viscous drag and turbulent decay (Greene, 1986). These models were subsequently extended adding ground and crosswind effects, eddy dissipation rate, variable vortex spacing and other parameters (Holzäpfel, 2003). Latest studies aim to cover as many as possible of so called first-order parameters: aircraft configuration, turbulence, stable stratification, shear, and proximity of the ground.

(Holzäpfel, 2003) defines a **Probabilistic Two-Phase Wake Vortex Decay and Transport Model** (P2P). In P2P model evaluation of vortex-pair circulation is averaged over circles with radii from 5 to 15 m. The model is based on vortex evolution equations. Vortex decay progresses in two phases, a diffusion phase followed by rapid decay. P2P also contains probabilistic components to account for the variability caused by vortex instabilities, deformations, and uncertainties regarding environmental conditions. The output of the model consists of lower and upper bounds for vortex position and strength. P2P accounts for all relevant environmental parameters, with the exception of wind shear.

NASA-Langley develops a numerical large-eddy simulation model called the **Terminal Area Simulation System** (TASS) (Proctor, 1996). The TASS model can simulate a variety of meteorological phenomenon including convective local storms, wind shear, hailstorms, etc. It can also be applied to aircraft wake vortex simulations. The TASS model is capable of simulating wake vortices for a wide range of atmospheric conditions that include: vertical wind shear, stratification, atmospheric boundary layer turbulence, fog, and precipitation.

Wake area models. NEXTOR's wake vortex models (Shortle et al., 2010) include a wake area – region of space behind an aircraft, in which another aircraft may encounter wake turbulence. Two approaches are suggested: fixed wake area and dynamic wake area. Fixed wake area model (Fig. 28, left) has fixed dimensions, based on appropriate wake characteristics. Many factors are ignored (wind, aircraft weight, etc.). In the dynamic model (Fig. 28, right) wake area is described as a 3D polyhedron. Polyhedron is a function of aircraft parameters (velocity, mass, wingspan, etc.), atmosphere (wind, air density, eddy dissipation rate, etc.) and circulation threshold (Shortle et al., 2010).

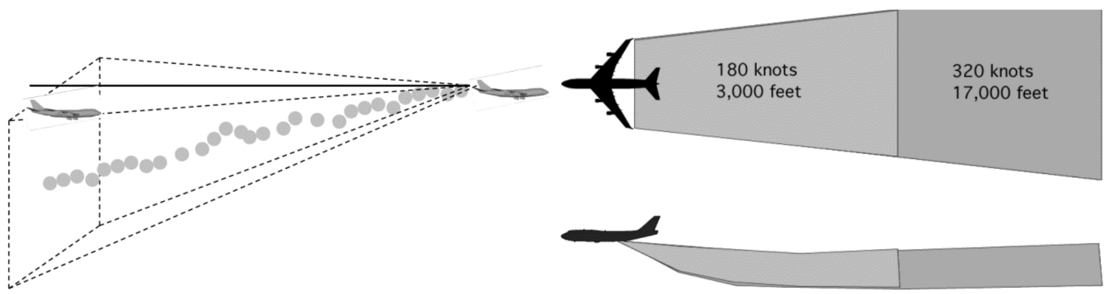

Figure 28. Fixed (left) and dynamic (right) wake area model (Shortle et al., 2010)

2.8 Conclusions

The research is at the intersection of several areas: decision support in real-time systems, modeling of aircraft trajectories, wake turbulence, aircraft conflict prediction, risk modeling, data fusion, and visualization.

CD&R systems is a common type of decision support in aviation related applications. The structure of the CD&R process (Kuchar & Yang, 2000) is designed for the aircraft separation conflicts, but can be expanded to cover other normative rules. Conformance alerting philosophy is suitable for the approach/departure norm supervising scenario: alert is issued when the aircraft is close to violating the norm.

Studies in human-automation interaction assert that high automation levels are not advisable in dynamic environments, such as the traffic control environment. This accords with the SESAR ATM target concept which states that humans shall play the central role in all decisions. This means, that the focus of the approach/departure DSS is on informing the controller rather than guiding his decisions.

The analysis of time critical decision-making models revealed the key features for the approach/departure DSS. First, from the human cognitive perspective, quick encoding is a key factor that facilitates human decision-making. This is achieved by providing an intuitive visualization. Since pictures are encoded faster than symbols, a requirement is to present information graphically. Second, naturalistic decision-making models in the context of tracking aircraft require presenting the airport procedures intuitively. From the modeling perspective, the procedures define a relation between aircraft track, distance from the runway threshold and altitude. Thus, a proper visualization of this relation is needed.

A visualization model has to be selected for the DSS. Due to technical constraints, complex augmented reality or other beyond-the-desktop solutions are not suitable. 2D visualizations in the ATM domain are no longer sufficient, and the modern 3D visualizations have drawbacks. Studies in similar projects demonstrate that it is possible to overcome these drawbacks by integrating 2D and 3D elements in the same screen. For this reason it was chosen to use a 3D screen (to visualize altitude dimension) and augment it with auxiliary 2D elements, so that it is possible to visualize the “ought-to-be” trajectory constraints: a relationship between horizontal position, distance and altitude.

One of the tasks is to model radar-lidar data fusion. The essential step in data fusion process is filtering. Out of the filters used in tracking systems, Kalman filter is often referred as the most accurate of the recursive filters, and to have better computation times than particle filter.

One of the specific norms to be modeled is the wake turbulence norm. In order to represent it in the DSS, some kind of wake area model is needed. A variety of modeling techniques are used to model wake turbulence – from generalized geometric representations, to complex atmospheric systems and probabilistic models. The approach/departure DSS, however, has only aircraft position and speed data. There is no data on weather, or aircraft configuration, so a simplified, position-based, wake area model will be needed.

3 Norm Violation Risk Modeling

This chapter presents the main theoretical results of current research. Section 3.1 describes the main assumptions of work, that influence normative rule modeling, violation risk visualization, and the development of the DSS prototype. Section 3.2 is dedicated to normative rule conceptualization, section 3.3 – characterization of norm violation risk, section 3.4 – norm violation risk visualization, section 3.5 – modeling of the approach/departure procedure constraints, and section 3.6 defines the steps for norm modeling in the DSS.

3.1 Assumptions

The research is based on the following assumptions:

1) **Use of lidar together with the primary radar**. Lidar is used together with the primary radar and thus provides aircraft position with a high degree of accuracy (meters). This enables to model fine-grained normative rules and constraints for the aircraft trajectories. It would not be possible to detect violations of these norms using solely radar data. Other measurement equipment could be used to obtain the accurate aircraft position, instead of the lidar. In either case, data fusion is needed to fuse the data from lidar (or other accurate surveillance equipment) and from the airport radar. If only the airport radar data is available, the norm violation risk model could also be applied. In this case, only some norms could be modeled in the DSS, and only significant violations would be detected. Such simplification would take out the practical significance of the task. The currently used tools are sufficient for the current ATC operation mode and additional support tools are not needed. Thus, the use of lidar is an important presumption of this work.

2) **DSS is a real-time system**. A real-time response is required from the DSS. A study of time-critical decision support models concludes that the naturalistic decision support approach should be used. The naturalistic approach suggests it is not feasible to fully quantify the situation and find a solution mathematically, but it is important to filter out the most relevant information

and thus facilitate the human in making a decision. Therefore, the risk model in the DSS is based on norm conformance and defines discrete risk levels to help comprehension. For simplicity, the “traffic-light” color scheme (three risk levels: ‘green’, ‘yellow’ and ‘red’) is used in visual indicators.

3) **DSS input**. The DSS receives aircraft position and speed data only. It comes from the lidar and the radar system. The input track data set is presented in Table 5. For full DSS input protocol specification, see Appendix 2.

Table 5. DSS input protocol

Track data set
Track ID
Time
Azimuth, Elevation, Range
Azimuth speed, Elevation speed, Radial speed
X coordinate, Y coordinate, Z coordinate
Speed along X axis, Speed along Y axis, Speed along Z axis
Last track update time
Track extrapolation indicator
Track fading number
Last not extrapolated measures (Time, Azimuth, etc.)

4) **DSS output**. DSS output consists of the fused position, detected norm violation risks and recommended actions. Data fusion flag indicates whether the fusion was performed, or the position data is equal to that of the original track data set. Up to two risks and recommended actions can be identified for each track data set (see Table 6). Full DSS output protocol specification is presented in Appendix 3.

Table 6. DSS output protocol

DSS output data set
Track ID
Time
Azimuth, Elevation, Range
Azimuth speed, Elevation speed, Radial speed
X coordinate, Y coordinate, Z coordinate

Speed along X axis, Speed along Y axis, Speed along Z axis
Radar-lidar data fusion flag
Event 1
Other track ID involved by event 1
Risk of the event 1
Actions for the event 1
Event 2
Other track ID involved by event 2
Risk of the event 2
Actions for the event 2

5) **Level of automation**. The emphasis is on detecting risk and informing the controller. The DSS system provides surveillance, evaluates and recommends, whereas the human controller takes a decision. There is no feedback loop from the pilot to the DSS (Fig. 29).

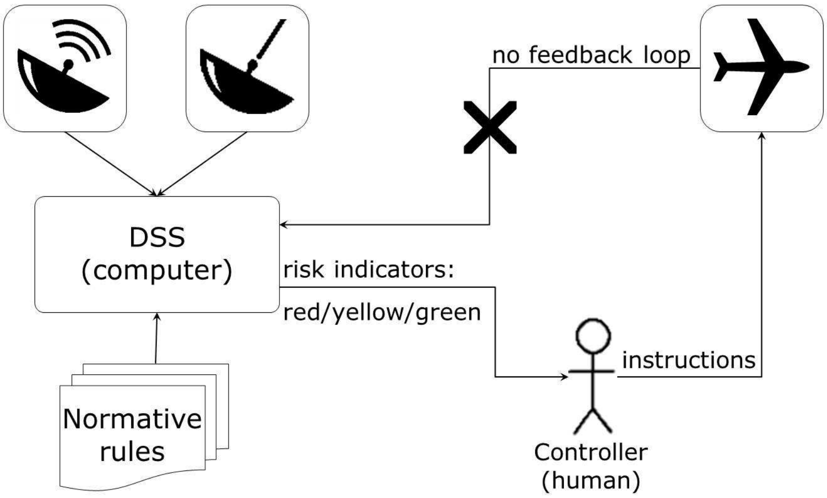

Figure 29. Role of the DSS in ATC context

This idea aligns with the results of current studies in human-automation interaction, and the SESAR ATM target concept. Using the terminology of (Kuchar & Yang, 2000), the system has a Conflict Detection threshold, but does not perform Conflict Resolution. Nevertheless, Conflict Resolution phase (the corrective action selection) is defined in the decision support process and the steps to generate recommended actions are sketched out. The full implementation and investigation of the corrective action mechanism could be the subject of further studies.

6) **Communication with other systems**. DSS is a component of a larger system (see Fig. 3). It receives input data and presents output data according to the specifications (see assumptions 3 and 4) and does not directly interact with other airport systems.

3.2 Norm Conceptualization

Normative rules for aircraft approach and departure are comprised of individual norms. The aim of this section is to distinguish the most granular item and characterize it. Norms are modeled in the context of radar and lidar data fusion and aircraft position prediction.

3.2.1 Norm Definition

Normative rules, for which the compliance can be evaluated using only aircraft position and speed data, are identified. This selection of approach/departure norms can be called "simple geometrical norms". Such normative rules include: separation norms, wake turbulence separation norms, speed, height and horizontal position restrictions in the airport procedure, horizontal and vertical profile of the procedure.

These individual norms state something about a certain trajectory parameter (e.g. "The descent angle shall be 3°"), or place a constraint on it (e.g. "The speed shall not exceed 210 kt"). The current research proposes to conceptualize each norm as a triplet (Fig. 30): norm factor, expected value, and a predicate.

Norm factor represents a quantitative attribute of the aircraft trajectory(ies). Only factors that can be computed from the DSS input data are considered.

The value which is used as a reference against the actual factor value is called an *expected value* of the factor (denoted v_N, normative value). Typically, the expected value is the number that is given in the norm (3° or 210 kt) or is derived from it.

Predicate explicates how to interpret the relation between the actual factor value and the expected value:

- '≤v_N' ('less than') – the actual value should be smaller than the expected;
- '≥v_N' ('greater than') – the actual value should be greater than the expected;
- '=v_N' ('equal to') – the actual value should be equal to the expected.

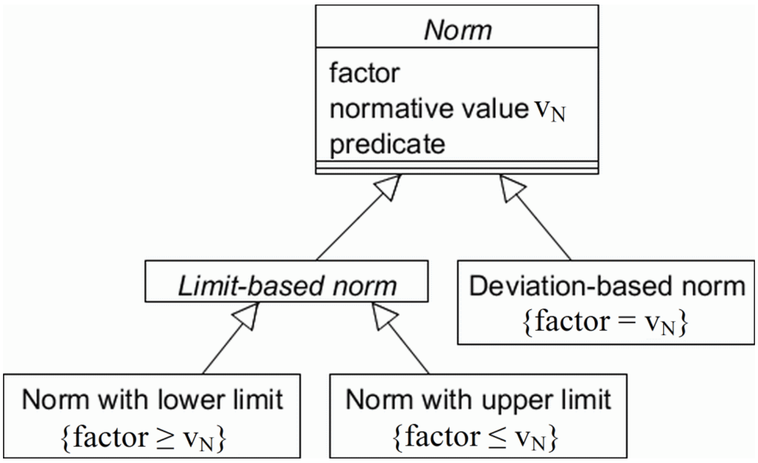

Figure 30. Normative rule modeling

Although three predicates are defined, the distinction between '≤v_N' and '≥v_N' is not substantial, so two norm types are distinguished. The two former predicates ('≤v_N' and '≥v_N') constitute *limit-based* norms, and the third predicate ('=v_N') constitutes *deviation-based* norms.

3.2.2 Examples of Different Norm Types

Examples of the limit-based norms

- "height minimum is 3900 ft. at 6 nautical miles from distance measurement equipment (DME)" (see Fig. 31, predicate is ≥v_N).

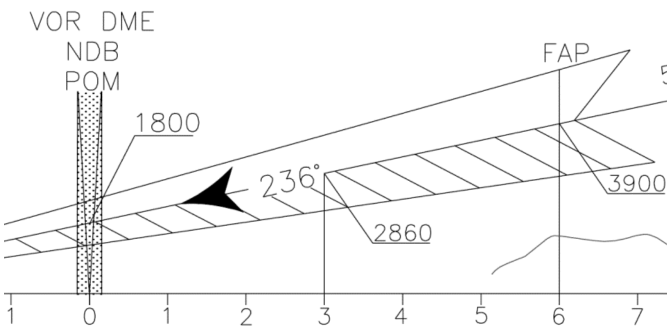

Figure 31. Minimum altitudes in the approach chart (VATITA, 2003, chart no. 351)

- “a minimum of 5.6 km (3.0 NM) radar separation shall be provided between aircraft on the same instrument landing system (ILS) localizer course” (ICAO Doc 4444, 2007, p. 123), predicate is $\geq v_N$;
- “maximum indicated airspeed (IAS) on turn from track 043° is 210 knots” (nautical miles per hour, see Fig. 32, predicate is $\leq v_N$);

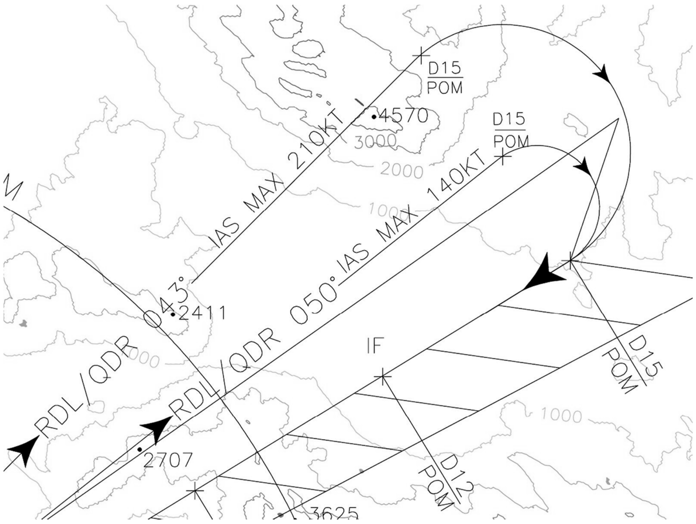

Figure 32. IAS constraint in the approach chart “IAS MAX 210KT” (VATITA, 2003, chart no. 351)

Examples of the deviation-based norms

- the glide-path (a descent profile determined for vertical guidance during the final approach (ICAO Doc 4444, 2007, p. 27), which is expressed in degrees and presented in the approach procedures, e.g. “GP 3.33°” (VATITA, 2003, chart no. 349);
- the track (the direction that the aircraft should follow), which is expressed in degrees from North, e.g. “236°” (VATITA, 2003, chart no. 351).

Determining the type of some norms may be ambiguous. For example, the height norm (“3900 ft at 6 DME” described above) defines the minimal allowed altitude value, which suggests that this norm is to be interpreted as a limit-based norm. However, if the aircraft altitude is much greater than the specified expected value, it will be unable to land. So, the norm can also be considered a deviation-based norm with tolerance for the negative deviation (observed values smaller than norm) smaller than for the positive deviation (observed values greater than the norm).

3.2.3 Examples of the Norms Not Covered

The three predicates do not cover all possible norms applicable in the aircraft approach/departure. Only norms for which the compliance can be evaluated using only aircraft position and speed data are covered. The examples that cannot be directly covered by this model include, but are not limited to:

- Complex, or non-precise geometry. When an aircraft has to make turn (e.g. as shown in Fig. 32), the maneuver is specified only with two headings – the one from which it starts, and the other it has to join. The actual trajectory of the maneuver will depend on the speed of the aircraft, the wind, etc. So, notwithstanding that the airport procedure depicts the curve of the turn, not every aircraft will duplicate it.
- Norms that explicitly state that any ATC instruction may be overridden:
    - "if an ACAS resolution advisory (RA) manoeuvre is inconsistent with the current ATC clearance, pilots shall follow the RA" (ICAO Doc 9863, 2006, p. 121).
- Norms that reference factors that the DSS doesn't have data about, e.g.:
    - "priority shall be given to an aircraft which anticipates being compelled to land because of factors affecting the safe operation of the aircraft (*engine failure*, *shortage of fuel*, etc.)" (ICAO Doc 4444, 2007, p. 141);
    - "flight operations are allowed in the EPZ, provided the operator follows the *recommendations of aircraft and engine manufacturers*" (EASA, 2010);
- Norms that have rulings based on human judgment or intentions, e.g.:
    - "an IFR flight may be cleared to execute a visual approach provided the pilot *can maintain visual reference* to the terrain" (ICAO Doc 4444, 2007, p. 115);
    - "if an aircraft enters an aerodrome traffic circuit without proper authorization, it shall be permitted to land if its *actions indicate that it so desires*" (ICAO Doc 4444, 2007, p. 141);

- Abstract rules, such as:
    - "aircraft that has the right-of-way shall maintain its heading and speed, but nothing shall relieve the pilot-in-command from the responsibility of taking such action as will best avert collision" (ICAO Annex 2, 2005, p. 21).
- Norms that do not cover all possible scenarios and because of that may possibly be disregarded in some situations. E.g., the norm "when two aircraft are approaching head-on or approximately so and there is danger of collision, each shall alter its heading to the right" (ICAO Annex 2, 2005, p. 21) doesn't cover multiple aircraft conflicts. The solution of such multi-conflicts may not always adhere to this rule for every pair of the converging aircraft (Fig. 33).

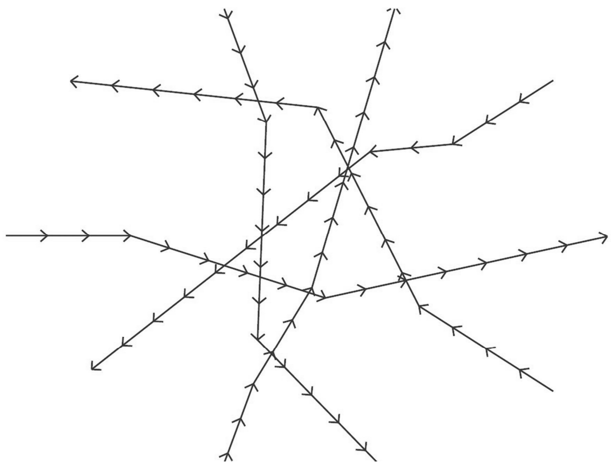

Figure 33. Example of 5 aircraft conflict resolution (Durand & Alliot, 2009)

3.3 Characterization of Norm Violation Risk

Only the norm itself was characterized above. Such norm definition is not sufficient to model norm violation risk yet. Further, norm violation risk model is developed and norm violation risk is characterized.

3.3.1 Risk item definition

Risk evaluation focuses on the events that may occur, their likelihood and impact (Mahler, 2009). In everyday usage, risk is often used synonymously with the risk impact dimension (the consequences). However, there is not enough data to reliably estimate possible norm violation consequences, which may vary from radiating acoustic noise in highly populated areas to disrupting the traffic in the ATZ (SKY-Scanner, 2007, p. 43).So, the norm violation risk model introduced in this section associates risk with the likelihood dimension of the risk definition.

The evaluation of norm violation risk associates some *event* and its *likelihood*. In the DSS, likelihood is defined as a measure how close the aircraft is to violating the norm (conformance approach, see 2.2.2). Likelihood is described qualitatively – using *risk levels*.

A separate risk item definition is formulated for each normative rule (the risk event may be denoted as '*norm-factor* violation'). In the DSS, an individual risk item evaluation maps the observed factor value to a discrete scale of risk levels. The minimum number of levels is two: 'no violation' when the norm is complied, and 'violation' when the norm is violated. This is not sufficient for human controllers. Several risk levels are needed to help the controllers prioritize the situations. Also, there is a need to know in advance, while the constraint is not yet violated, but there is a risk of violation. The levels of the traffic light model may be used: 'red', 'yellow', and 'green'. In general, there may be as many discrete levels, as needed.

The risk item definition ties together the norm and the risk levels. Thus, the L-level risk item definition is characterized by five elements (Fig. 34):

1) norm factor (e.g. 'altitude' or 'indicated airspeed');
2) predicate ('greater than', 'less than', or 'equal to');
3) expected value of the factor;
4) type ('limit' or 'deviation');
5) a set of thresholds for risk levels;

If the risk type is "limit", a set of thresholds consists of L-1 constants, defined in the terms of factor measurement units. If risk type is "deviation", a set of thresholds consists of L-1 pairs of constants, defining allowable deviation levels. The threshold values in the following examples are chosen for demonstration purposes only and are subject to fix by experts.

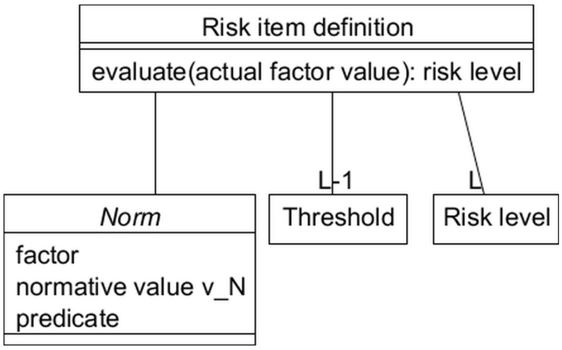

Figure 34. Proposed characterization of the risk item definition

For convenience of visual representation of the risk item definition, a ranking function (Fig. 35) is defined, which maps the observed factor value to a number from the interval [0, 1]. Zero means the lowest level (e.g. ‘green’ or ‘no risk’), and 1 means the highest level (e.g. ‘red’ or ‘risk’). The real function of norm violation probability is unknown. In the DSS, as a piecewise linear function is chosen as a ranking function. This is sufficient, because the likelihood level is of interest, not the value of probability.

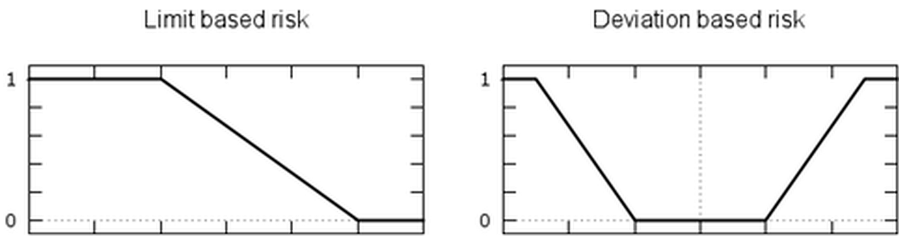

Figure 35. General ranking function for the two risk types

3.3.2 Limit-based Risk

The definition of the **volcanic ash zones** (see Fig. 10) is an example of a limit-based normative rule. Risk item could be defined according to the concentration levels provided in (UK CAA, 2010): ‘green’ (normal operations zone), ‘red’, ‘grey’, and ‘black’ (no-fly zone). As there are four risk levels (L=4), there are three thresholds: $v_0 = 2x10^{-4}g/m^3$, $v_1 = 2x10^{-3}g/m^3$, and $v_2 = v_N = 4x10^{-3}g/m^3$ (Fig. 36).

The corresponding risk item definition is: (1) norm factor: ‘volcanic ash concentration’; (2) predicate: ‘$\leq v_N$’; (3) expected value: $4x10^{-3}g/m^3$; (4) type: ‘limit’; (5) thresholds: $v_0 = 2x10^{-4}g/m^3$, $v_1 = 2x10^{-3}g/m^3$, $v_2 = 4x10^{-3}g/m^3$.

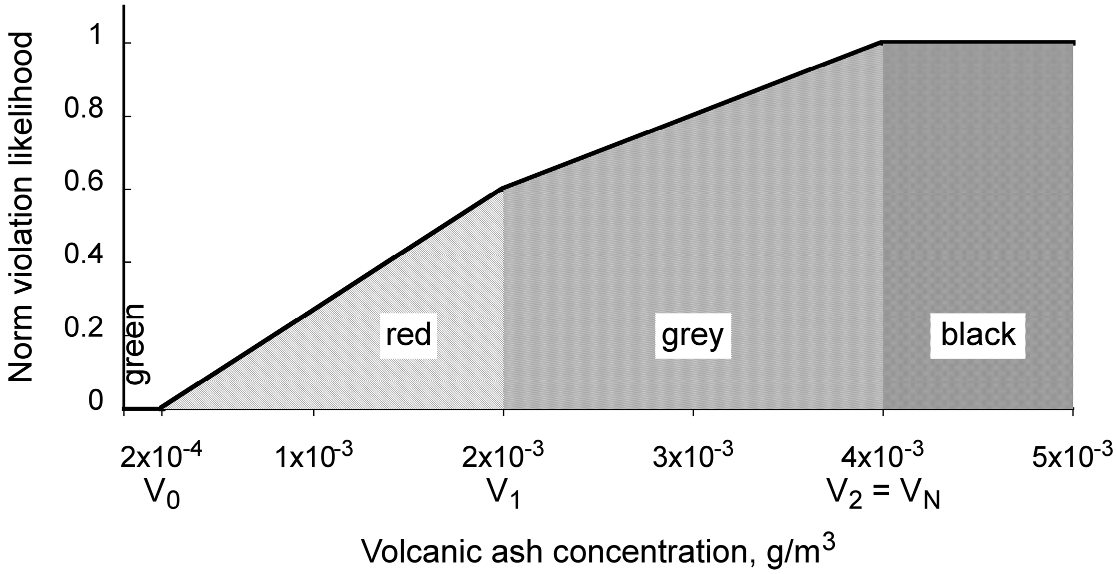

Figure 36. Volcanic ash concentration norm-violation modeling

As a second example, the **indicated airspeed norm** is considered: “maximum indicated airspeed (IAS) on turn from track 043° is 210 knots” (Fig. 32). Four risk levels (L=4) are defined: ‘white’ (no risk), ‘green’, ‘yellow’, and ‘red’ (maximum risk). There are three (L–1) thresholds (Fig. 37): v_0 (v_{LOWER}) – threshold for detecting possible violation risk, v_1, and v_2 (v_{UPPER}) – threshold for signaling high risk. The thresholds can be expressed in terms of deviations from the normative value v_N: $v_0 = v_N - \Delta_0$, $v_1 = v_N - \Delta_1$, $v_2 = v_N + \Delta_2$.

Segments of the ranking function, representing the risk levels are:

- ‘white’: $[0, v_0]$;
- ‘green’: $[v_0, v_1]$;
- ‘yellow’: $[v_1, v_2]$;
- ‘red’: $>v_2$;

The corresponding risk item definition is: (1) norm factor: ‘indicated airspeed’; (2) predicate: ‘$\leq v_N$’; (3) expected value: 210 kt; (4) type: ‘limit’; (5) thresholds: v_0 = 202 kt, v_1 = 206 kt, v_2 = 214 kt.

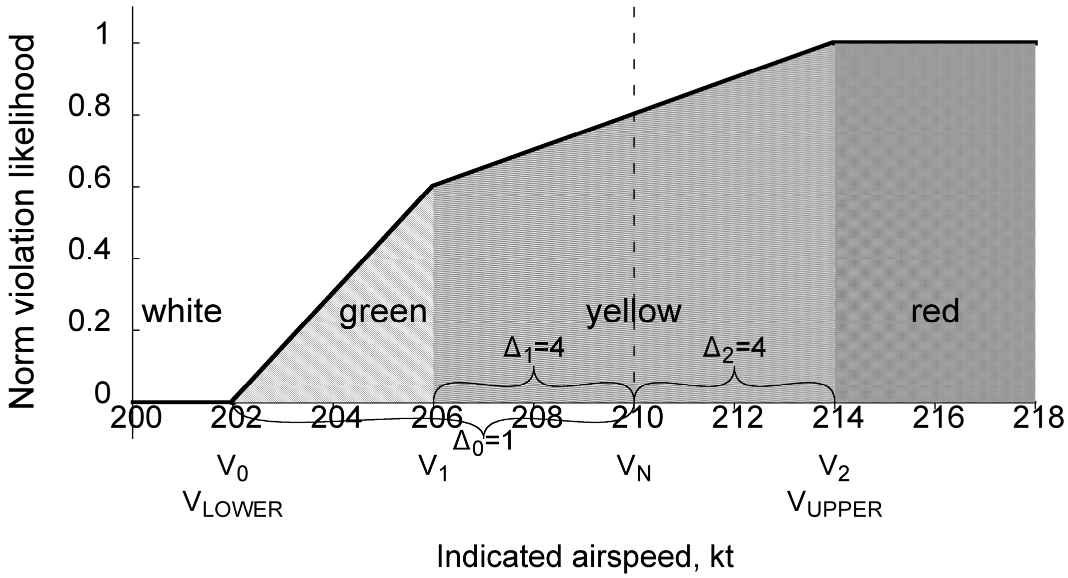

Figure 37. Indicated airspeed norm violation modeling

3.3.3 Deviation-based Risk

In this example the **altitude norm** is considered: "altitude 3900 ft at 6 DME" (Fig. 31). In deviation-based norm violation evaluation, the expected deviation (d_N = 0) is of interest, rather than the expected value itself. There are four levels and three pairs of thresholds: d_{n0} and d_{p0} (thresholds for detecting possible violation risk), d_{n1} and d_{p1}, and d_{n2} and d_{p2} (thresholds for signaling high risk). The d_{ni} are "negative" thresholds, i.e. for values smaller than the norm, and d_{pi} are "positive" thresholds, i.e. for values greater than the norm. The thresholds can be expressed in terms of allowable deviations: $d_{n0} = d_N – \Delta_{n0}$, $d_{p0} = d_N + \Delta_{p0}$, $d_{n1} = d_N – \Delta_{n1}$, $d_{p1} = d_N + \Delta_{p1}$, and $d_{n2} = d_N – \Delta_{n2}$, $d_{p2} = d_N + \Delta_{p2}$. Segments of the ranking function, representing risk levels are (Fig. 38):

- 'white': [d_{n0}, d_{p0}];
- 'green': [d_{n1}, d_{n0}] or [d_{p0}, d_{p1}];
- 'yellow': [d_{n2}, d_{n1}] or [d_{p1}, d_{p2}];
- 'red': <d_{n2} or >d_{p2};

The corresponding risk item definition is: (1) norm factor: 'altitude'; (2) predicate: '=v_N'; (3) expected value: 3900 ft at 6 DME (deviation 0); (4) type: 'deviation'; (5) thresholds: d_{n0} = –0.5, d_{p0} = 2, d_{n1} = –1, d_{p1} = 3.5, d_{n2} = –1.5, d_{p2} = 5.

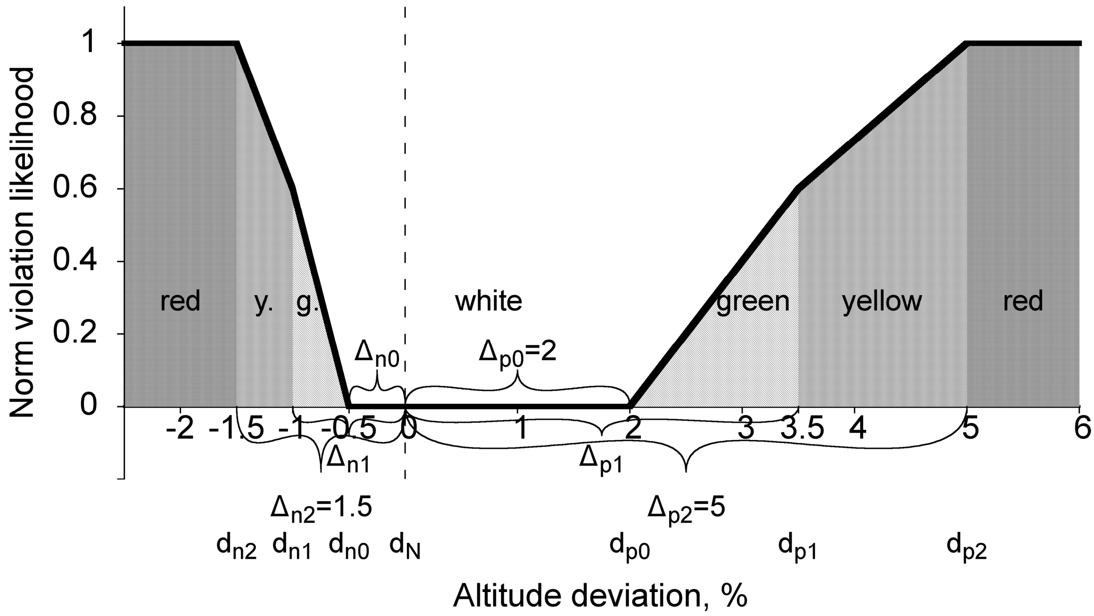

Figure 38. Altitude norm violation modeling

Another example is the **glide-path** norm. Glide-path is a descent profile determined for vertical guidance during the final approach. It is expressed in degrees and printed in the approach procedures, e.g. "GP 3.33°" (VATITA, 2003, chart no. 349). As with the previous risk item definition there are three pairs of thresholds (Fig. 39).

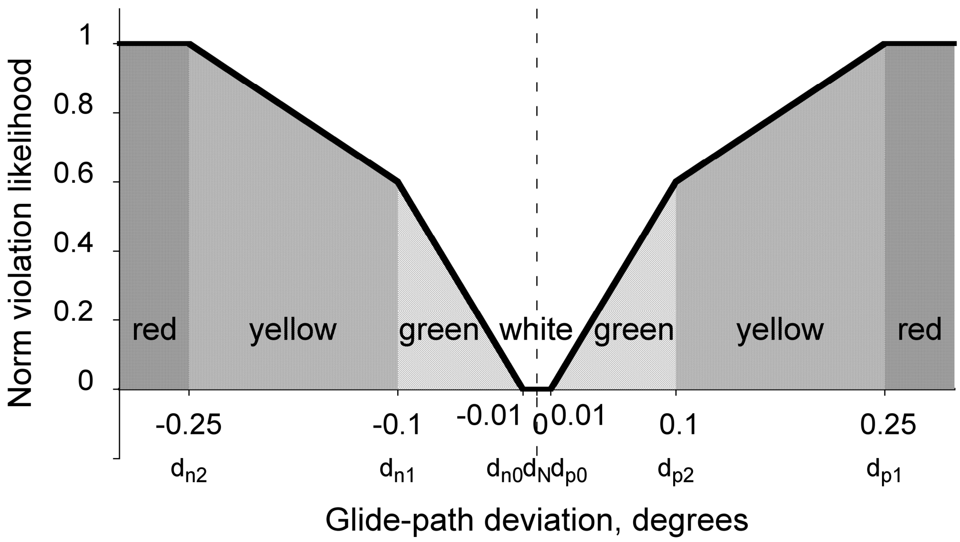

Figure 39. Glide-path norm violation modeling

The corresponding risk item definition is: (1) norm factor: 'glide path'; (2) predicate: '=v_N'; (3) expected value: 3.33° (deviation 0); (4) type:

‘deviation’; (5) thresholds: d_{n0} = –0.01, d_{p0} = 0.01, d_{n1} = –0.1, d_{p1} = 0.1, d_{n2} = –0.25, d_{p2} = 0.25.

3.3.4 Aggregated Risks

Some norm violations could be related not to one, but to several norms. Aggregation of separate risk item definitions is needed when the norm violation event happens only when several constraints (norms) are violated simultaneously. For example, aircraft separation violation happens only when both horizontal and vertical separation constraints are violated. The aggregated risk item definition (Fig. 40) ties together two risk item definitions and adds a rule how the risk level are combined to obtain the aggregated risk level.

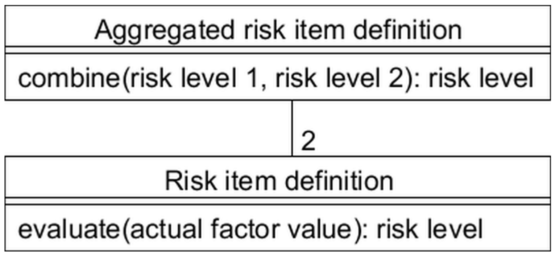

Figure 40. Proposed modeling of aggregated risks

For example, if the separation risks have three levels (‘red’, ‘yellow’ and ‘green’), they could be combined in this way: if both are ‘red’, the overall risk is ‘red’, if at least one is ‘yellow’, the overall risk is ‘yellow’, if both are ‘green’, the overall risk is ‘green’.

3.4 Norm Violation Risk Visualization

The result of risk evaluation is visualized (i.e., presented for visual cognition) to the controller. This section demonstrates how the norm violation risk model is employed in the decision support scenario. The initial user feedback was positive for the decision support scenario involving the presented risk model.

Traffic-light risks. The traffic-light model (see section 2.6) is proposed to indicate norm violation likelihood level and guide controller decisions. Each risk item definition has a corresponding colored indicator on the DSS control panel. As in the usual traffic-light model, *red* color indicates corrective actions are required, *yellow* draws attention to the potential threats, and *green* indicates violation risks that can be disregarded at the moment. Fourth color – *white* – is added to indicate likelihood that evaluates to zero or normative rules not relevant at the moment. Consider two aircraft that are too far apart to consider risk of separation loss, or path violation risk for an aircraft that has not started executing the approach procedure yet. The risk levels have to be mapped to the four traffic light colors.

Decision support scenario. A general configuration of the user interface is presumed: the information is presented in two views, (1) the observed airspace view, that visualizes a map and the tracked trajectories, and (2) a control panel (Fig. 41) which contains indicators for each risk, and additional detail data. In the observed airspace view the aircraft indicator changes its color according to the worst risk, calculated for that track. This color serves to attract attention, and the particular risk can be determined by looking at the control panel.

Path violation risks are tracked for one aircraft (primary track) when an airport procedure is assigned to it. Typical scenario is: (1) select primary track; (2) assign procedure (Fig. 42).

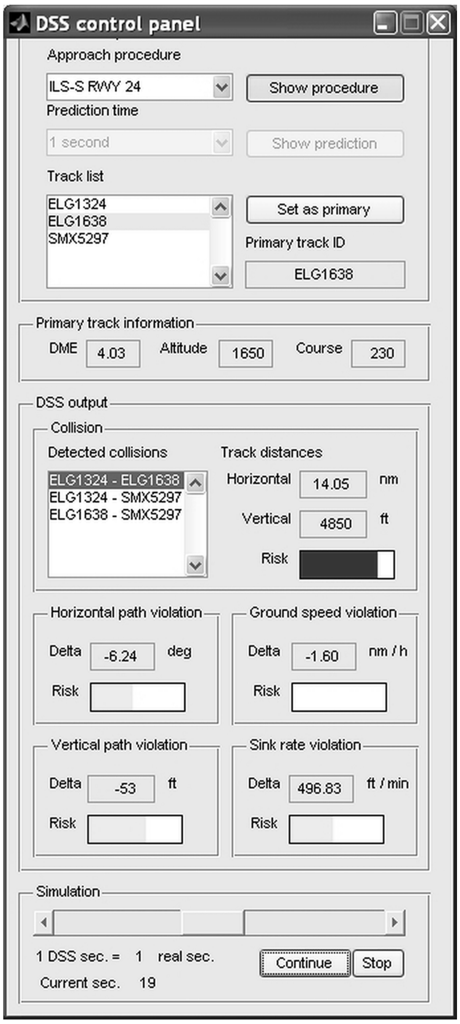

Figure 41. Example of the DSS control panel

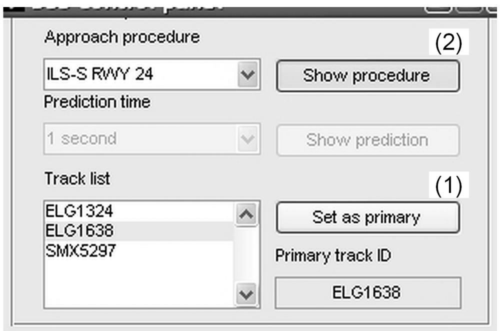

Figure 42. Top part of the control panel

When the procedure is selected, the system tracks values of the factors prescribed in the procedure: course, altitude, glide path, etc. Violation risks are shown in individual indicators (Fig. 43). “Delta” field shows the difference between the normative value and actual value.

Figure 43. Path violation risk indicators: continuous (left) and discrete (right)

Continuous indicators. Continuous indicators show value of the ranking function with the size of the slider (portion of the indicator which is colored). The risk level is shown with color of the “Risk” slider.

Discrete indicators. As an alternative, discrete risk indicators were designed. Consider, for example, eight risk levels: ‘W0’, ‘G1’, ‘G2’, ‘Y3’, ‘Y4’, ‘Y5’, ‘R6’ and ‘R7’. A discrete indicator is divided into seven segments (Fig. 44). In this scheme, risk level names encode the representation with graded indicators. Number in the risk level name means how many segments are colored, and the letter encodes what is the color of the last colored segment (W – white, G – green, Y – yellow, and R – red). When risk level is ‘G1’, first segment is colored in green. When risk level is ‘G2’, first two segments are colored in green. When risk level is ‘Y3’, first two segments are colored in green, and the third is colored in yellow.

Figure 44. Discrete risk indicator examples

Risk indicators for aircraft pairs. For the risks factors involving two aircraft (i.e. separation), all pairs are examined, and pairs where risk is detected are shown in a list (Fig. 45). After selecting one list entry, an indicator and the details of detected risk are displayed.

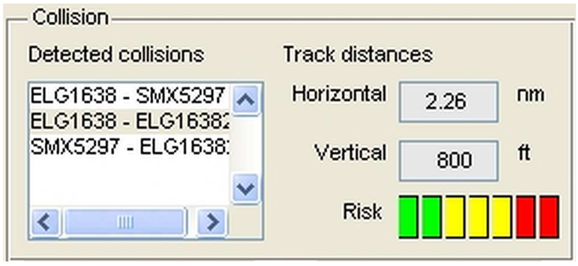

Figure 45. Collision risk indicator example (with discrete indicators)

3.5 Approach/Departure Constraint Modeling

3.5.1 Flight Phase Model

Phase of flight refers to a period within a flight. Most of aviation related systems record the phase of flight to classify events. Not all systems use the same criteria for these categories. Different taxonomies emerged due to the use of synonyms, and different perspectives (e.g. pilot or ATC).

A flight phase model is proposed to categorize the normative rules. It is based on the flight phase model from the Common Taxonomy Team (CAST/ICAO CTT, 2011) which aims to provide unambiguous definitions and to cover all aspects of flight. For complete description of CTT model see Appendix 4.

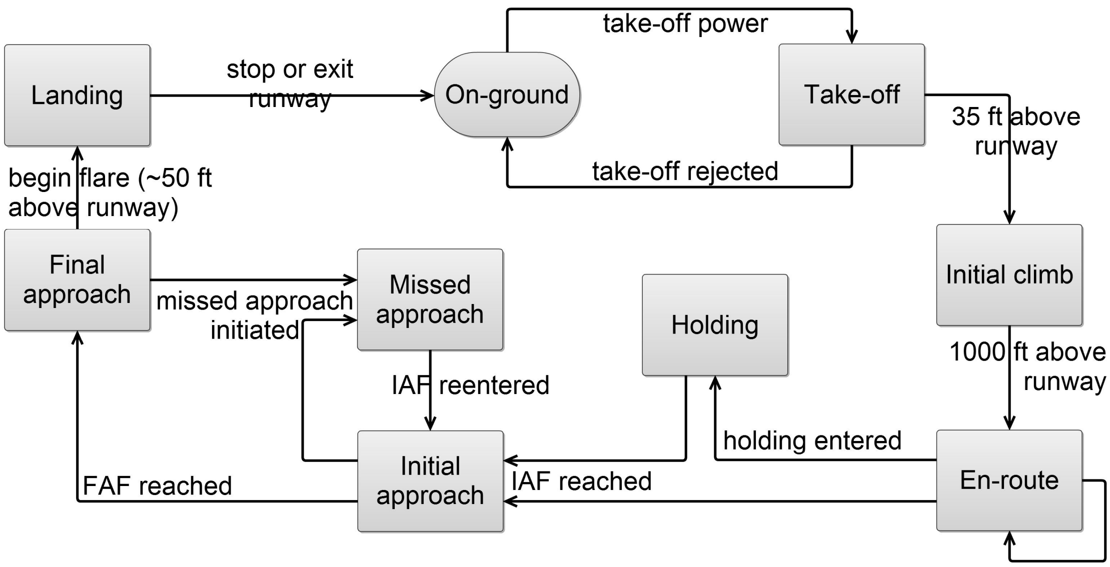

Figure 46. Proposed flight phase model compliant with (CAST/ICAO CTT, 2011) (Legend: FAF – final approach fix, IAF – initial approach fix)

The flight phase model which is shown in Fig. 46 was developed in the current research. It includes the phases that are relevant to the approach/departure scenarios. CTT on-ground phases (standing, pushback/towing and taxi) are grouped into one phase. Holding sub-phase is separated from the en-route phase, as holding is an important part of the approach procedures. Table 7 shows correspondence of the proposed flight phase model and different flight phase taxonomies.

Table 7. Proposed flight phase classification in comparison to other models

Proposed flight phase model	**Common taxonomy** (CAST/ICAO CTT, 2011)	**ATC clearances** (ICAO Doc 4444, 2007)	**Instrument procedures** (ICAO Annex 4, 2009)	**ACAS event reporting** (ICAO Doc 9863, 2006)
On-ground	1. Standing, 2. Pushback/towing, 3. Taxi	1. Taxi	Phase 1: Taxi from aircraft stand to take-off point	
Take-off	4. Takeoff	2. Take-off	Phase 2: Take-off and climb, Phase 3: En-route, Phase 4: Descend to approach	1. Departure (take-off to 10 000 ft), 2. Climb, 3. Cruise, 4. Descend (to 10 000 ft)
Initial Climb	5. Initial Climb	3. Departure		
En-route	6. En-route: (a) Climb to cruise, (b) Cruise, (c) Change of cruise level, (d) Descent	4. En-route		
Holding	6. En-route: (e) Holding			5. Holding pattern
Initial Approach	8. Approach: (a) Initial Approach	5. Approach	Phase 5: Approach to land and missed approach	6. Approach (below 10 000 ft)
Final Approach	8. Approach: (b) Final Approach			
Missed Approach	8. Approach: (g) Missed Approach			
Landing	10. Landing	6. Landing	Phase 6: Landing and taxi to aircraft stand	
(not covered)	7, 8: c through f, 10 through 12, and 13			

3.5.2 Approach Constraint Model

Approach phases terminate on fly-over points that have associated constraints. Each specific approach procedure determines the number of points. The following approach constraint model is developed (see Fig. 47).

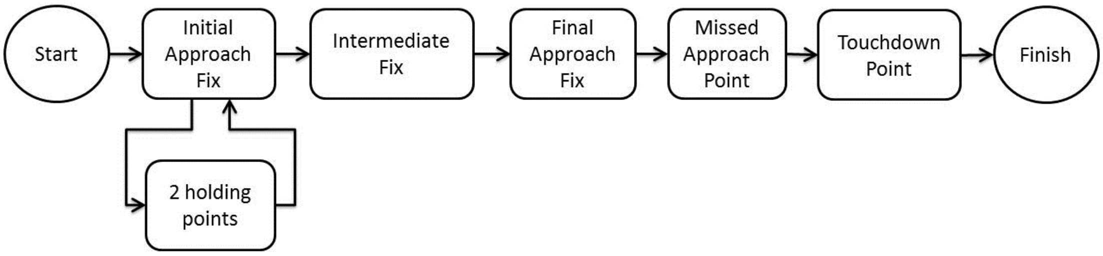

Figure 47. The approach procedure is modeled in terms of fly-over points

Two types of constraints define the approach procedure:

1. Global: defined for the whole procedure;
2. Local: defined for the particular fly-over point.

Global attributes are the following:

1. Name of the procedure;
2. Glide Path (GP in degrees or GP INOP in %);
3. Reference Datum Height (RDH);
4. Obstacle Clearance Altitude/Height (OCA/H) for each aircraft type;
5. Sink Rate (SR, in feet per minute) for a given Ground Speed (GS);
6. Time needed to fly between defined points for a given GS;
7. Runway orientation (in degrees).

Summarizing the fly-over point constraints the approach procedures were concluded to have the following local attributes:

1. Name of Distance Measuring Equipment (DME) device (required);
2. Name of a fly-over point (optional);
3. Lateral distance to DME (required);
4. Lateral distance to Touchdown Point (TP) (required);
5. Altitude (required);
6. Course or track (required).

Table 8 provides an example of local constrains for Napoli/Capodichino airport approach procedures through IAF “Bento” fly-over point. The table is interpreted the following way: if the aircraft is flying according to the ILS-P procedure, the course should be 236°, and, for example, at the distance of 13 nautical miles to the airport, the aircraft's altitude should be 4830 feet (see table line 3).

Table 8. Example of approach procedure local constraints (Napoli/Capodichino)

No.	**Reaching point type and name if available**	**ILS-P procedure for Runway 24 DME INP**		**Track**
		DME, nautical miles	**Alt, feet**	°
1.	IAF "Bento"	19	7000	236
2.	IF	16	5900	236
3.		13	4830	236
4.	FAF	10	3770	236
5.		7	2730	236
6.		5	2000	236
7.		4	1646	236
8.		3	1293	236
9.		2	939	236
10.		0.8	504	236

3.5.3 Departure Constraint Model

Unlike approach, the departure is not broken down into separate sub-phases. The "ought-to-be" trajectory of the departure is defined by an ordered list of reaching points with associated constraints.

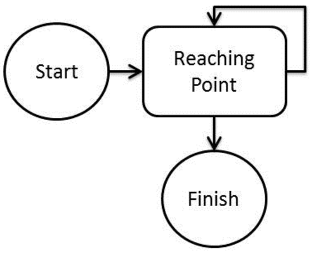

Figure 48. The departure procedure is modeled in terms of reaching points

The following departure constraint model is developed (see Fig. 48). For instrument departures the following constraints are defined:

1. Initial track (degrees);
2. First fly-over point (distance, altitude);
3. Turn direction (left, right);

4. Turn track (degrees);
5. Second fly-over point (distance, altitude);
6. Track to follow (degrees);
7. Next fly-over point (minimum crossing altitude in ft);
8. Minimum climb gradient (ft/nm);
9. Required altitude (ft);
10. Turn speed (indicated airspeed, IAS, in kt).

Summarizing, the following data are involved: sequence number, reaching point name with distance and altitude constraints, fly-over (yes/no), course/track to follow (angles), turn direction and speed constraint.

Table 9 provides an example of constrains for the Napoli/Capodichino airport standard instrument departures from runway RWY 06.

Table 9. Example of standard instrument departure constraints (Napoli/Capodichino)

Initial track	**No.**	**Reaching point**	**Dist.**	**Alt, ft**	**Fly-over**	**After turn direct.**	**To track, °**	**IAS const-raint, kt**	**Minimum climb gradient, ft/nm**
057	1	POM VOR/NDB (D5 NPC DME)	D 5	1500	Y	Left	210	230	300 (5%)
	2	RDL/QDR 342 SOR VOR/NDB		2300			162		
	3	GEMMA		3500	Y		162		
	4	SOR VOR/NDB		6000	Y				

The table is interpreted the following way: if the aircraft is departing from runway RWY06, the initial track is 057° until point POM VOR/NDB is crossed at 1500 ft or above, then the aircraft has to turn left and proceed on track 210° until joining RDL/QDR 342 SOR VOR/NDB (TR 162°). The latter is not a fixed point on the map, but rather a spot where the aircraft intercepts the specified heading on the specified radio beacon. Then, the aircraft has to cross point GEMMA at 3500 ft and point SOR VOR/NDB at 6000 ft.

3.5.4 Approach/Departure Norm Factors

Based on the ATC separation rules and the airport charts, ten norm factors are identified:

1. Vertical position
    1.1. Altitude
    1.2. Glide-path
    1.3. Obstacle clearance
2. Speed
    2.1. Climb gradient
    2.2. Indicated airspeed
3. Horizontal position
    3.1. Course
    3.2. Maneuver area
    3.3. Circling sector
4. Take-off
    4.1. Time-based separation
    4.2. Take-off direction

Table 10 maps the identified norm factors to the flight phases in which they are applied (note: on-ground and landing phases do not have any associated factors). These factors roughly cover the perception of the “ought-to-be” trajectory and set boundaries of the path violation problem-space. Calculation of the actual value of some factors may be complex, for example, time-based separation should involve some sort of trajectory prediction.

Table 10. Norm factors applied in different flight phases

Norm factor	Take-off	Initial climb	En-route	Holding	Initial approach	Final Approach	Missed Approach
1.1 Altitude		X	X	X	X	X	X
1.2 Glide-path						X	
1.3 Obstacle clearance		X					
2.1 Climb gradient		X					X
2.2 Indicated airspeed		X		X			X
3.1 Course		X	X	X	X	X	X
3.2 Maneuver area				X			
3.3 Circling sector				X			
4.1 Time-based separation	X						
4.2 Take-off direction	X						

3.6 Steps for Norm Representation in the DSS

To represent a normative rule in the approach/departure DSS the following steps are performed:

1. Setting up the risk representation structure:
   1.1. Determining the number of risk levels, L.
   1.2. Associating each level with one of the colors ‘white’, ‘green’, ‘yellow’, and ‘red’.
2. Creating risk item definitions. For each individual normative rule:
   2.1. Defining norm factor and the expected value. Defining norm factor involves specifying how the actual factor value will be calculated from the DSS input data.
   2.2. Stating the norm type and the predicate.
   2.3. Defining L–1 thresholds (for limit-based norm), or pairs of thresholds (for deviation based norm).
3. Setting up a risk indicator for each risk item definition.

Incorporating different risks. The norms govern the behavior of humans (pilots, controllers), and not all of them are translatable to technical rules. Subsection 3.2.3 presents examples of normative rules that cannot be directly represented in the proposed model. Such norms could be represented in an expanded model, which may be based on “if-then” rules and not centered on technical rulings. For example, every risk item definition could be represented as a set of “if-then” rules of the form “IF <actual-factor-value> is less | greater than <threshold$_1$> THEN likelihood := <level$_2$>”. The other, not “simple geometrical”, norms would have a simpler form, only two risk levels (e.g. ‘violation’ and ‘no violation’). For example, norm about ACAS RA and ATC clearance contradiction could be expressed like this “IF <acas-ra> ≠ <atc-clearance> THEN likelihood := ‘violation’ ”.

3.7 Conclusions

The approach/departure decision support focuses on detecting violations of the normative rules for the aircraft. A conformance-based alerting model is chosen. Four factors are supposed including the loss of separation and path violation. Norms are modeled from the perspective of violating them. The defined model translates each norm into a risk item definition in the DSS. Two norm types are identified: limit-based and deviation-based. Each norm is modeled with a factor, normative value v_N, and a predicate. The use of discrete norm violation likelihood levels abstracts from unnecessary details. Currently each norm results in a separate indicator.

The results of this chapter were published in (Lapin, Čyras & Savičienė, 2012), (Lapin, Čyras & Savičienė, 2011), (Savičienė, Operationalization of Norms…, 2011), (Savičienė, 2010), and (Savičienė, 2012).

4 Decision Support System Prototype

This chapter presents the decision support system prototype. The DSS prototype is developed with a purpose to validate the proposed method demonstrate feasibility of its implementation. Section 4.1 describes the prototype scope, requirements and data model. Section 4.2 is dedicated to the decision support process structure implemented in the prototype. The discrete Kalman filter is applied in the DSS prototype to solve two distinct problems: radar-lidar data fusion, and aircraft position prediction. Section 4.3 describes modeling of radar and lidar data fusion, and section 4.4 – modeling of aircraft trajectory prediction. Section 4.5 is dedicated to corrective action selection.

4.1 DSS Prototype Scope, Requirements and Data Model

4.1.1 Scope and Constraints

The DSS prototype software is developed to elaborate and validate the proposed normative rule modeling and norm violation risk visualization, and to demonstrate feasibility of system implementation. The prototype simulates DSS operation and visualizes approach/departure scenarios with respect to several norms.

To demonstrate the proposed norm violation risk model, the following groups of norms were modeled and implemented in the prototype system: horizontal and vertical separation, approach procedures, wake turbulence separation and ash clouds. The prototype demonstrates:

- Modeling of the selected norms.
- Norm violation likelihood evaluation for these norms.
- Visualization of the observed airspace and the aircraft positions.
- Notification of detected violations to the controller.

The prototype is currently adapted to airports of Pescara and Napoli. Napoli/Capodichino airport sample day radar data archive was available for prototype verification.

The actual DSS is expected to be a part the overall airport air traffic management (ATM) system. The main task of the DSS is to generate risk messages for the controllers. Externally operation of the DSS prototype simulates the operation of the actual DSS, i.e. the DSS prototype analyzes the input data informs the controller of detected violations in real-time.

The internal structure of the DSS prototype will be as simple as possible, data structures may not mimic those expected of the actual DSS. Only main functions will be implemented. The emphasis is on information visualization. The DSS prototype has a graphical interface and presents most of the information to the user graphically. Textual form will be used to present the results of calculations, detailed information on the observed aircraft, and some short messages.

The DSS prototype is developed in Matlab environment. Matlab provides an interpreted programming language that is designed for mathematical calculations, but not well adapted to real-time systems. Therefore, performance of rendering 3D moving objects is quite low. It was decided to use a Matlab add-on Virtual Reality Toolbox. This library provides an interface linking Matlab algorithms to 3D graphics objects. Objects are represented in the Virtual Reality Modeling Language (VRML), and can be animated by changing properties such as position, rotation, and scale during desktop and real-time simulations. The chosen environment had some influence on choosing the visualization of the GUI objects.

4.1.2 Summary of Requirements and Architecture

The DSS prototype shall meet the following **functional requirements**:

1. Read input data and write output data as a series of records in CSV file format provided in Appendix 2 and Appendix 3.
2. Perform data fusion of radar and lidar data.
3. Visualize positions of the tracked aircraft with respect to the runway in the graphical user interface (GUI) window.

4. Perform risk evaluation for:
    a. Horizontal and vertical separation
    b. Airport approach procedures
    c. Wake turbulence separation
    d. Volcanic ash cloud
5. Evaluate overall risk for each tracked aircraft.
6. Display the evaluation results in the control panel.

The DSS prototype shall meet the following **non-functional requirements**:

1. Process one data record no longer than one second.
2. The prototype shall be developed in Matlab version 7.0.1 (R14) or later.

The user of the DSS prototype shall be able to perform the following:

1. Start and stop the simulation.
2. Change observation angle and distance.
3. Select one aircraft as primary and assign a specific approach/departure procedure to it.

Fig. 49 shows main use cases of the DSS prototype. The runway can be used by a single aircraft at one moment. It receives the ATC clearance to take-off or land. SPS prototype assumes that the aircraft is assigned either approach or departure procedure. The prototype evaluates aircraft position deviations from the chosen procedure (path violation). Other types of violations (separation, wake turbulence, etc.) are evaluated for all aircraft all the time.

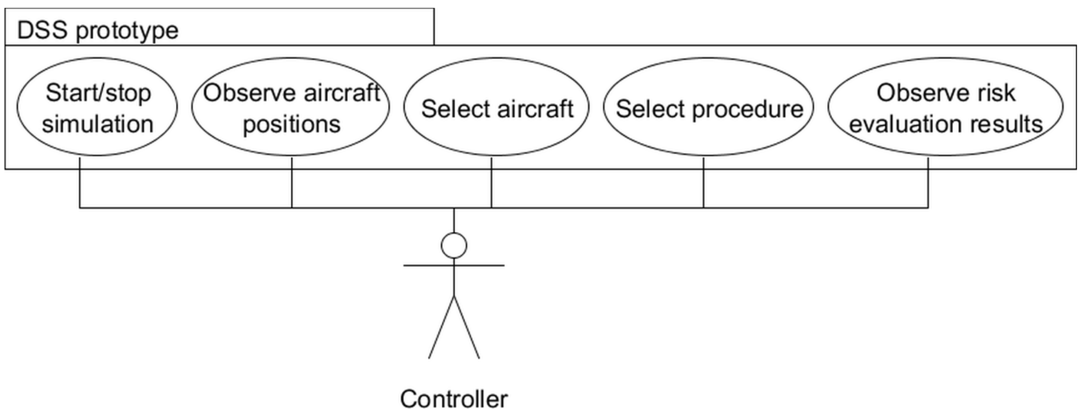

Figure 49. The DSS prototype use cases

The DSS prototype has three layers:

1. User interface layer
2. DSS functionality layer
3. Data exchange layer

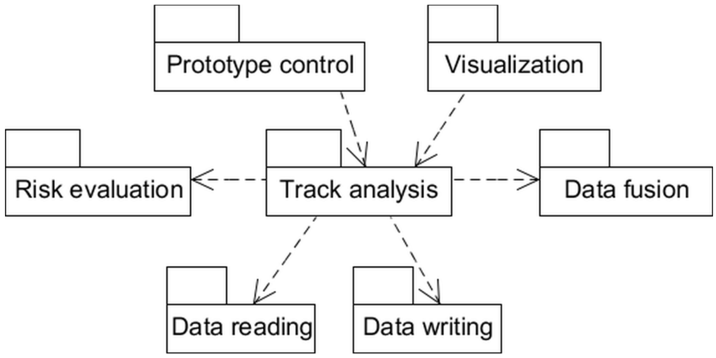

Figure 50. Package structure of the DSS prototype

Each layer acts as a server to the upper level layer, and as a client of the lower level layer. The user of the prototype interacts only with the first layer. User interface layer has two components: prototype control and visualization. DSS functionality layer has three components: track analysis, data fusion and risk evaluation. Data exchange layer has two components: data reading and data writing. Fig. 50 shows DSS prototype components.

The prototype control component uses track analysis component to start and stop the simulation and to set the parameters (primary aircraft and selected approach procedure). Visualization component uses track analysis component to get aircraft positions and evaluated risks for displaying. Track analysis component uses data reading component to get radar and lidar track data, data fusion component to get the fused position, risk evaluation component to evaluate each individual risk and calculate an overall risk level, and uses data writing component to write results.

4.1.3 Data Model and Graphical Interface

The primary DSS prototype data model is represented in Fig. 51. The main entity that the DSS deals with is the *trajectory*. Trajectory is comprised of 3D *positions*. Aircraft trajectories are visualized with respect to the *terrain* in order to show the altitude information. The *airport* to which the DSS is adopted has its own set of *airport procedures*. Each procedure establishes some *reference trajectory* (the “outght-to-be” trajectory). In order to represent it in the DSS, the 3D-position-based representation of the reference trajectory has to be derived from the procedure constraints. The observed *aircraft* has a *current position*, the *past trajectory* (composed of previous positions), and the *predicted trajectory* (if prediction is turned on). One of the observed aircraft may be selected as *primary aircraft*. When a specific procedure is assigned to the primary aircraft, the DSS tracks path violation according to that procedure.

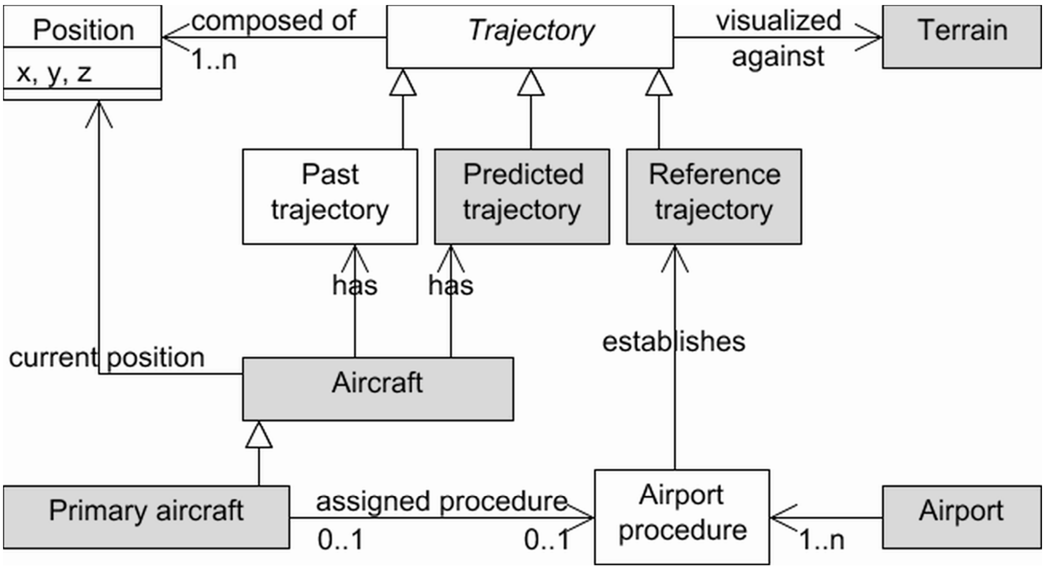

Figure 51. The proposed DSS data model

The DSS prototype exchanges information with the external systems using CSV files. One line in the CSV file corresponds to one *data record*. *Input data record* has either *radar data*, or *lidar data*, which provides the DSS with the aircraft position. *Output data record* includes the fused position and the *event*, in case some risk was identified for the corresponding input position.

The DSS prototype processes a lot of data every moment – aircraft coordinates, past and projected trajectories, risk alerts etc. Some information is presented in a separate (flight data) display. However, switching from one display to a separate information source could be time consuming and taking attention away from the traffic situation. So, on one hand, it would be beneficial to visualize on the main screen as much information, as possible (Lange et al., 2003). On the other hand, it is important not to clutter the display. Here, visualization alternatives for the identified GUI objects are reviewed.

Aircraft is the main object in the DSS system interface. An aircraft indicator will denote the current position of the observed aircraft. Aircraft indicators can have different levels of detail: like points (spheres in 3D), like wedges/cones or 3D models of the aircraft. Wedge/cone is better than a point because the apex can show the direction of the aircraft. If the aircraft is represented as a 3D model, aircraft type could be easily recognizable. Also, some additional information could be attached to it, like the airline label (Bourgois et al., 2005), although such level of detail can be distracting. The 2D-in-3D prototype uses the sphere indicators, and the pure 3D prototype uses the 3D models. Additional calculations are needed to properly orient the 3D model.

Past trajectories. Older analog radar CRT displays showed a trail of blips left by an aircraft – their direction and distances apart, which provided cues for controllers about the direction and the speed with which an aircraft was travelling (Wong et al., 2007). Displaying past trajectories could make the DSS more acceptable to the controllers. Line and dotted line representations of past trajectories were used in the early throwaway prototypes of the DSS (Fig. 52). Studies have shown that the past trajectory visualization with lines has both advantages and disadvantages from the human-computer interaction point of view. Due to selected modeling environment, past trajectory lines would be tricky to render. Also, such lines, although they look natural in 2D views, are inconvenient to interpret in 3D views.

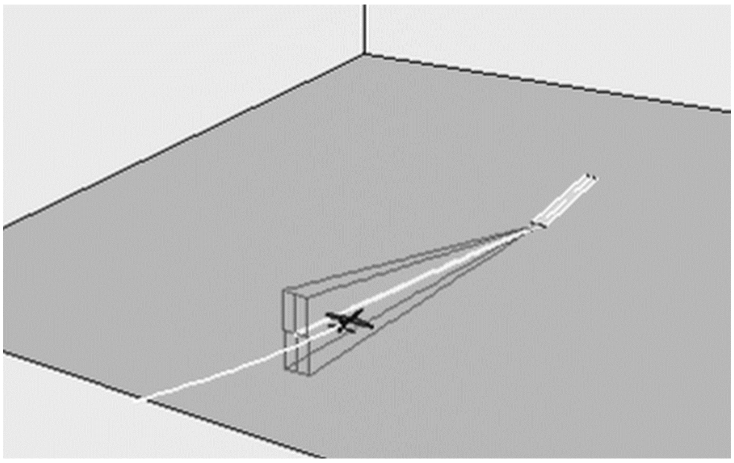

Figure 52. Example of the past trajectory visualization (solid white lines indicates the "ought-to-be" trajectory and the past trajectory)

Projected trajectories. As the DSS prototype has to predict the aircraft positions some time into the future to estimate possible violations, it should visualize the projected trajectory. In most reviewed examples the projected trajectory was represented as a segment extending from the aircraft's position (nose), which would be recalculated each time a new measurement of the aircraft position is received. Some authors propose to draw a "ghost plane" in front of the real plane, showing the projected position. Projected trajectory is represented in the 2D-in-3D prototype as a series of "ghost spheres", first sphere represents projected position after 1 second, second sphere represents projected position after 2 seconds, etc. As the "ghost spheres" introduce clutter into the display, the prediction (and its visualization) can be turned on or off using a button on the control panel.

Terrain. One of the benefits of 3D displays is the possibility to represent three-dimensional ground surface with actual elevation data (Rozzi et al., 2007). Although, some authors argue that it provides little useful information to the controller and suggest using a simple colored height map instead (Lange et al., 2003). The airports, for which the DSS prototype is configured, are not far from the mountains and it could be important to precisely show the terrain. The 2D-in-3D prototype uses a generalized terrain, and the pure 3D prototype uses a photographic map.

Approach/departure procedures ("ought-to-be" trajectories) are visualized to allow visual estimation of path violation, without looking at the control panel. The 2D-in-3D prototype represents the "ought-to-be" trajectory as a line on a projection curtain, and the pure 3D prototype encloses the "ought-to-be" trajectory in a series of wireframe rings. The solutions are presented in detail in subsection 5.1.2 and 5.1.3.

Identified GUI objects are shown in Fig. 51 with darker background.

4.2 Decision Support Process

This section describes the elements of the decision support process for aircraft approach/departure. The aim is to detect violations of normative rules. This problem can be abstracted to the same decision making problem as conflict detection and resolution (CD&R).

The general approach to normative rule modeling is the following: each norm is represented as a risk item definition in the DSS; when a new aircraft position is received, the risk evaluation process iterates through every risk item definition and estimates norm violation likelihood levels (Fig. 53). The purpose of the process structure is to show the place of the risk item definitions in the context of the overall decision support process (DS process). The CD&R process structure (see Fig. 12 on page 30) from (Kuchar & Yang, 2000) is adopted tailoring it to the aircraft approach/departure domain, and the use of lidar for aircraft tracking.

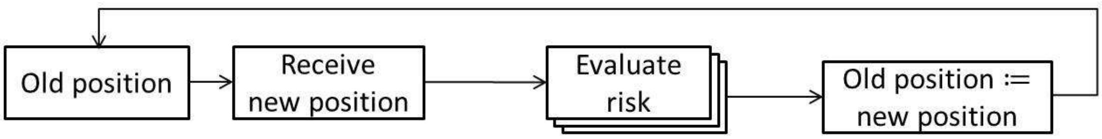

Figure 53. Risk evaluation loop

Conflict definition. From now on a broader and more general definition of a conflict is assumed: "a conflict is an event in which an aircraft experiences a loss of minimum separation to some hazard". What is a "hazard" could be separately defined for each type of normative rules (see Table 11).

Table 11. Conflict definition examples for different normative rules

Type of normative rules	Possible definition of a conflict
Horizontal and vertical aircraft separation minima	Loss of minimum separation to another aircraft (traditional view of CD&R)
Wake turbulence avoidance separation	Loss of minimum separation to wave vortices left by another aircraft
Procedure tracks	Loss of minimum separation to the edge of the path defined by the procedure. The trajectory, that the aircraft has to follow may be imagined not as a line, but as a tube, such that the aircraft should always fly inside the tube. So, a conflict would be loss of separation to the edge of the tube.
Altitude constraints	Loss of minimum separation to the terrain (as in ground proximity warning systems)
Volcanic ash related restrictions	Loss of minimum separation to the area where particle concentration exceeds the norm

Kuchar & Yang define the following phases: state estimation, dynamic model, metric definitions, conflict detection and conflict resolution. This model is tailored according to the assumptions from section 3.1 and a process of the decision support for aircraft approach/departure is defined (see Fig. 54).

Data fusion (state estimation). Aircraft position data is received from two tracking devices – radar and lidar. The state estimation phase consists of fusing data from radar and lidar and providing an adjusted position. The state information involves both horizontal and vertical planes (type HV according to Kuchar & Yang classification).

Prediction (dynamic model). The dynamic model projects the aircraft state information into the future. The word "prediction" is used to indicate the state propagation process. Conflict detection and resolution in ATC is done in three different layers, based on the time horizon considered (Chaloulos et al., 2009): long-term (horizon of hours – flow management problems), mid-term (horizon of tens of minutes) and short-term CD&R (horizon of minutes). In the case of aircraft approach and departure, the considered time horizon is even shorter. For example, a landing aircraft normally flies 6 NM in 2 to 5 minutes. The approach/departure DSS aims to detect short-term, or very-short-term conflicts, employing worst-case or probabilistic state propagation methods wouldn't give a significant advantage. So, a nominal prediction method is used (Fig. 13, a).

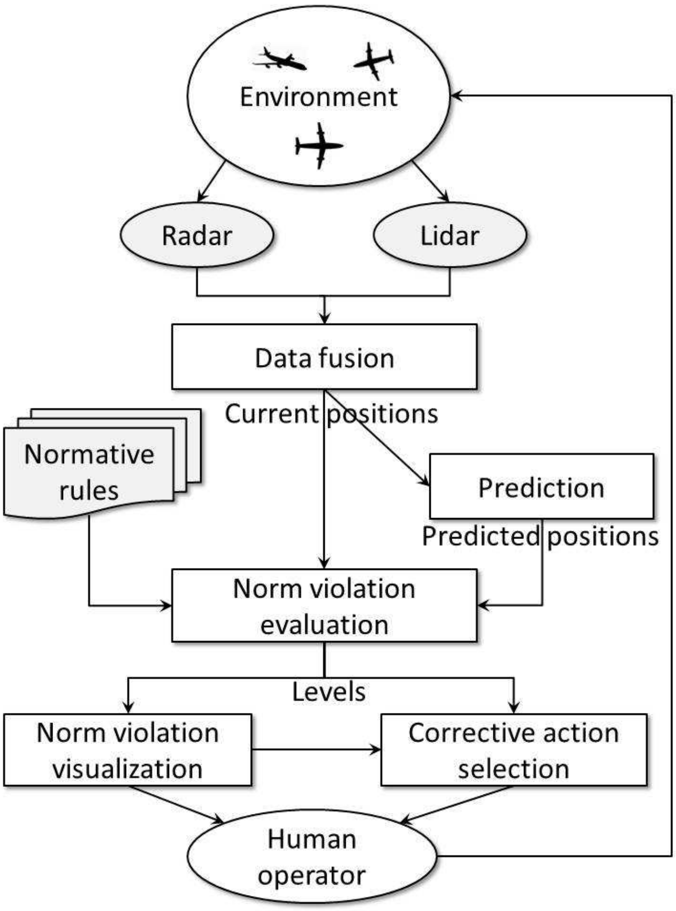

Figure 54. Proposed Interpretation of the Decision Support Process

Norm violation evaluation (metric definition). All metrics used in the proposed decision support process are expressed as risk item definitions. Each normative rule is represented as a risk item definition in the system. The risk evaluation calculates a discrete risk level for each risk item definition. These risk levels are used as decision thresholds in the subsequent phases.

Norm violation visualization (conflict detection). The conflict detection threshold is not explicit. A risk indicator is always shown for each risk. Risk indicator changes color and appearance according to the risk level. When the indicator is red, a corrective action should be generated.

Corrective action selection (in the context of conflict resolution). Conflict resolution step generates corrective actions. As the current research is focused on norm operationalization, this phase is only sketched out. The maneuvers that can be generated are prescribed (P) in advance (type P conflict resolution, according to Kuchar & Yang classification). Speed changes (S), turns (T), or vertical maneuvers (V) may be suggested as actions (type STV according to Kuchar & Yang classification), but no simultaneous or combined maneuvers are generated. Note, that there is no feedback from the human operator back to the conflict resolution component.

4.3 Modeling of Radar and Lidar Data Fusion

Kalman filter is applied in the DSS to solve radar and lidar data fusion problem. The DSS receives radar and lidar measurements in real-time as a series of aircraft position coordinates (x, y, and z) and several parameters such as speed projections. Radar data is received approximately every 5 seconds, and the lidar gives a measurement every second (SKY-Scanner, 2007).

The DSS does not implement the full data fusion process. According to the assumptions, the DSS is one of the data fusion nodes. Data alignment and association are done by the command and control computer. The presumed data fusion architecture is hierarchical with feedback (Fig. 55). The DSS receives track data prepared for the filtering.

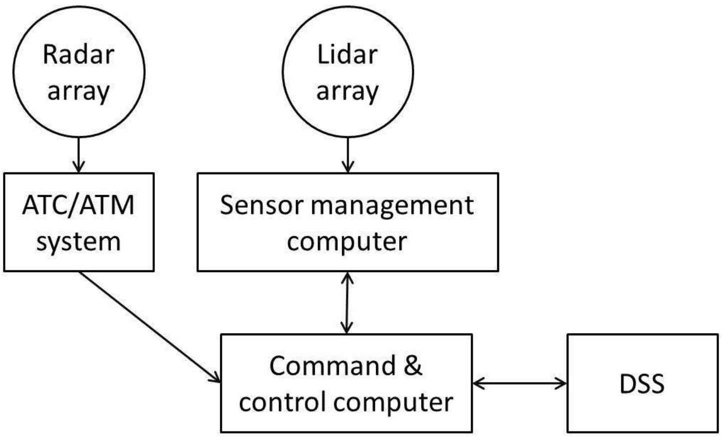

Figure 55. DSS in the context of radar-lidar data fusion architecture

Every second the DSS checks whether a measurement is received. If not – the aircraft position is predicted according to the internal model. When the measurement comes, it is fused with the internal model value. The following model is used for the fusion:

$$P_{fusion} = C_{radar} \times P_{radar} + C_{lidar} \times P_{lidar} + C_{model} \times P_{model}$$

where P_{fusion} is the fused aircraft position, P_{radar} – radar data, P_{lidar} – lidar data, P_{model} – internal model value, and C_{radar}, C_{lidar}, C_{model} – fusion coefficients.

The discrete Kalman filter is applied for the data fusion in the DSS prototype. The filter estimates the process state at a given time and also receives (noisy) measurements. The measurement update incorporates a new measurement into the a priori estimate. An improved a posteriori estimate is obtained next.

The discrete Kalman filter requires defining the noises of the measurement and the process. Radar and lidar measurements have different ranges of error. The measurement noise covariance is set from the device documentation. The determination of the process noise covariance is more difficult as we typically do not have the ability to directly observe the process we are estimating. The process noise covariance was estimated by tuning filter parameters. They were pre-computed off-line using the Napoli/Capodichino airport sample day data. With the process noise covariance Q = 0.01, the prediction (see solid line in Fig. 56) fully covers the measurements (see small circles in Fig. 56) of the turning aircraft. Other values (presented with asterisks and dots in Fig. 56) underestimate the measurement reliability and, therefore, the two predictions diagrams are imprecise. The measurement noise is stable (R = 0.01).

Sources quote the disadvantages of the Kalman filter: necessity of previous knowledge about the estimated process, and inability to manage complex scenarios (see section 2.5). These disadvantages are disregarded in this context based on the following work assumptions: a new measurement is received about every second, and lidar gives precise aircraft coordinates. Under the first assumption, a simple aircraft movement model is sufficient. Complex scenarios are not needed. The process noise estimate computed by tuning the filter parameters may not be accurate. However, under the second assumption, greater weight can be assigned to the lidar measurements, thus reducing the influence of the process noise.

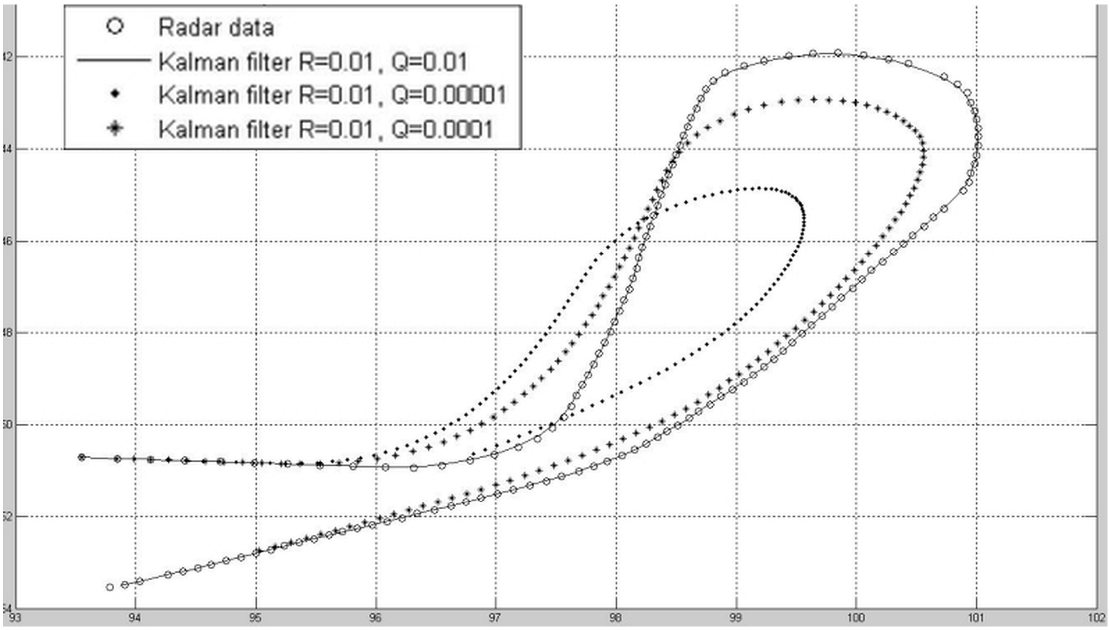

Figure 56. An example of the tuning of a process noise

4.4 Modeling of Aircraft Trajectory Prediction

Aircraft trajectory prediction problem is a separate problem from radar-lidar data fusion. Trajectory prediction problem is part of the risk evaluation problem and stems from it. To evaluate the norm violation risk, not only current position, but also the predicted position is of interest. ACAS systems work similarly. For example if an object is moving fast and accelerates at the current moment, there is a possibility that it will be moving too fast and thus violate the speed norm in the future.

The discrete Kalman filter is applied also for the trajectory prediction problem in the DSS prototype, as it can tune to the trajectory changes and potentially is better for predicting aircraft maneuvers than, e.g. simple linear extrapolation.

In the following example instantaneous speed predictions are used in Kalman filter update step to refine the position estimate. The instantaneous speed prediction algorithm is as follows.

When the new measurement is received from radar or lidar, instantaneous speed is calculated according to the change in the coordinates and time between measurements. The first measurement is considered to have instantaneous speed of zero.

Starting from the third measurement, predictions of the future speed are made as a square extrapolation of the last three instantaneous speed values. The coefficients of the speed variation formula are obtained using quadratic equation system, and are recalculated after each new measurement.

Legend (for Fig. 57 and further figures in this section): green asterisk (*) represents real trajectory data points, blue plus sign (+) represents the predictions using Kalman filter. Fig. 57 shows Kalman filter predictions when the speed is constant. When the speed is constant or almost constant (smooth movement), there is no deviation of prediction from the real data.

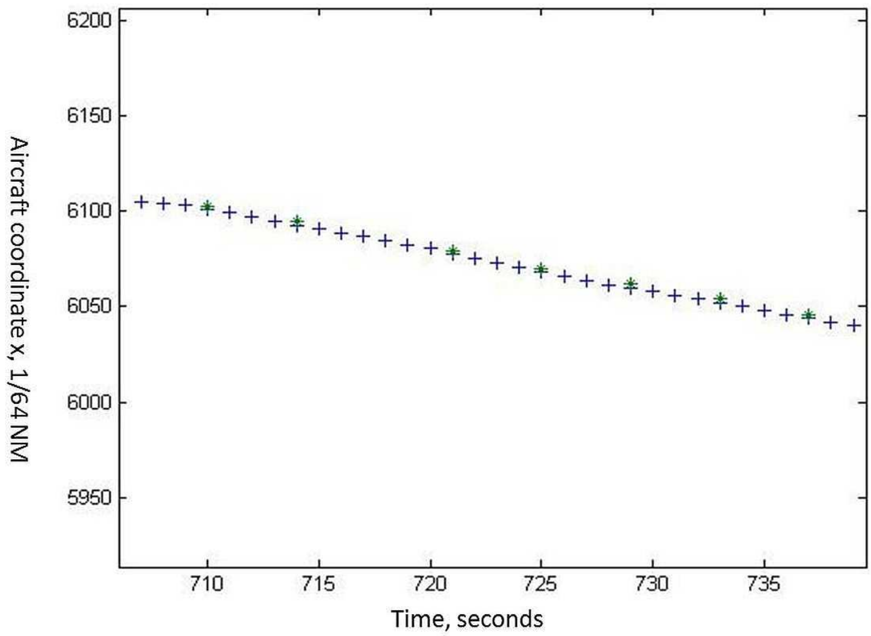

Figure 57. Trajectory prediction using Kalman filter, constant speed

Fig. 58 shows Kalman filter predictions when the speed is not constant, but the speed variation is uniform. The more uniform speed variation is, the better predictions are made. In both examples the speed variation is close to being uniform, and the deviation between predictions and real trajectory data is minimal.

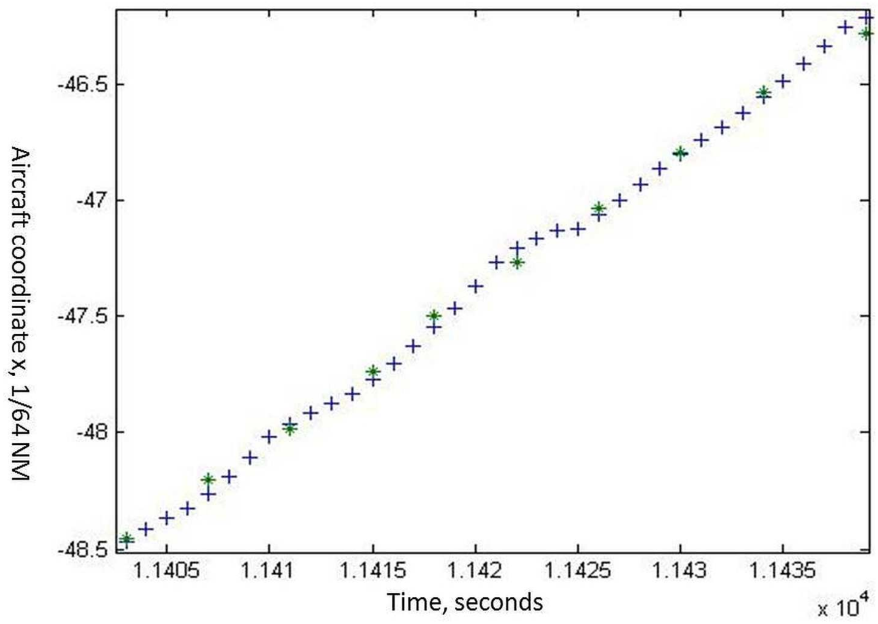

Figure 58. Example of trajectory prediction using Kalman filter, speed variation is uniform

When the speed variation is not uniform, the predictions become less precise. Fig. 59 presents an example where the speed increases sharply, and then suddenly decreases again. In this case, prediction deviates significantly from the real data. The algorithm is constructed in such a way that when speed increases it is expected that it will continue to increase. But in spite of the deviations, when the speed stabilizes, predictions become precise again.

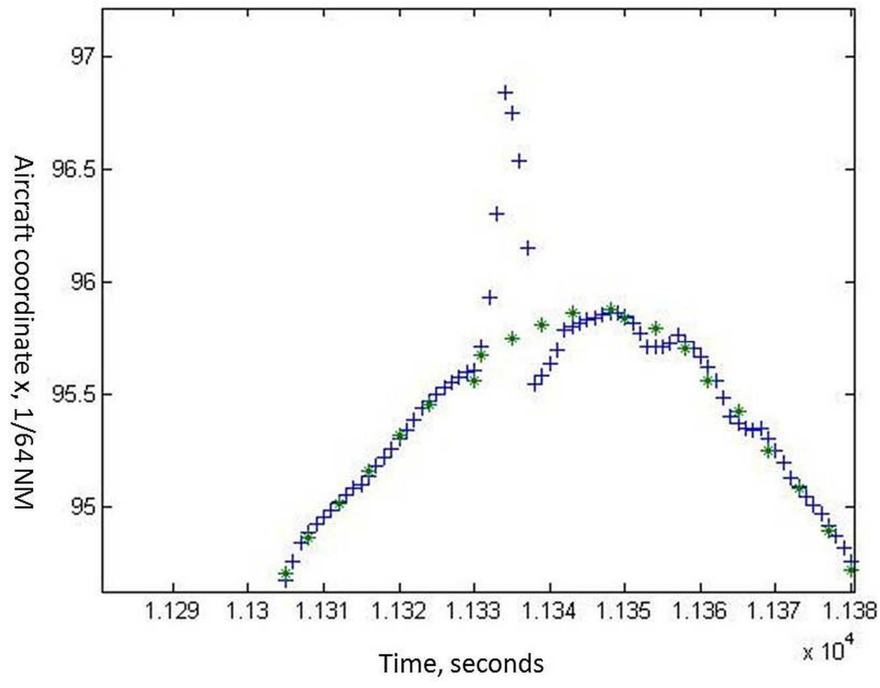

Figure 59. Trajectory prediction using Kalman filter, speed variation is not uniform

These examples show that Kalman filter is suitable for predicting both linear and turn trajectories when the speed is uniform or speed variation is uniform. When the speed variation is not uniform, there are deviations, but if non-uniform variation is short-term, the deviations are local and have little effect on further predictions.

4.5 Corrective Action Selection

Possible corrective actions. Typically conflicts are resolved by three different actions: turn, climb/descend, accelerate/decelerate, which affects the aircraft heading, altitude and speed respectively. It is found in (Hoekstra et al., 1998) that climb/descend is the most efficient action for resolving short term conflicts, since horizontal separation rules are more stringent than the vertical one (Alam et al., 2005).

If instrument rules are used, the controller usually doesn't give instructions after the aircraft intercepts the glide-path. In a broader range the choice of instructions may also be limited. For example, only minor speed adjustments are recommended in the intermediate and final approach; speed control should not apply to the aircraft on final approach that are closer than 4 NM to the threshold (ICAO Doc 4444, 2007, p. 55).

Corrective actions generated by the DSS. Therefore, actions generated by the DSS are simple. The supposed scenario is that the actions given by the DSS are only suggestions. This scenario accords with the observation that the controller should not be forced to stick to the system's decisions, as this has negative impact on his skills (Helmke et al., 2009).

The DSS generates short actions for risks with highest levels (e.g. "red" and "yellow"). In the case of risks related to trajectory parameters, actions tell to correct the parameter under concern. For example, turn left or right, adjust altitude (climb or descend), increase or decrease horizontal or vertical speed. If the involved aircraft is in the final approach phase (where maneuver possibilities are limited), and the risk level is the highest (e.g. “red”), missed approach action is suggested.

In the case of risks involving several aircraft (i.e. separation), vertical maneuvers are suggested as actions. As the aircraft must follow only predefined routes in the airport traffic zone, horizontal maneuvers are not considered. In these cases action may be specified for both aircraft involved.

Relative priorities of risks. Because several risks can happen at the same time, DSS chooses one of the events to generate actions for. Action is generated for the risk with the highest level. If several risks have the same highest level, a priority order is used. Here is the risk priority order (from highest to the lowest) used in the DSS prototype: loss of separation risk, wake turbulence risk, glide-path violation risk, obstacle clearance violation risk, altitude violation risk, climb gradient violation risk, circling sector violation, indicated airspeed violation, course violation risk. This is an example priority order, risks should be ordered by the experts in the production system.

Actions for the risk of path violation are chosen according to these principles:

- If the target aircraft is in the final approach phase, the missed approach should be initiated;
- If the target aircraft is in a phase other than final approach, the violated path parameter should be corrected.

Time-based separation violation for taking-off aircraft and take-off direction violation currently are not considered in corrective action selection.

Table 12. Possible corrective actions for path violation risk

No.	**Violation type**	**Possible actions**
1.1.	Altitude violation	Adjust altitude (climb or descend); if aircraft is in final approach phase – initiate missed approach
1.2.	Glide-path violation	Initiate missed approach (this violation occurs only in final approach phase)
1.3.	Obstacle clearance violation	Adjust altitude (climb)

No.	Violation type	Possible actions
2.1.	Climb gradient violation	Adjust vertical speed (increase)
2.2.	Indicated airspeed violation	Adjust airspeed (slow down)
3.1.	Course violation	Turn to remain on the specified course (left or right); if aircraft is in final approach phase – initiate missed approach
3.2.	Maneuver area violation	Turn to remain in the maneuver area (left or right)
3.3.	Circling sector violation	Turn to remain in the circling sector (left or right)

Actions for the risk of separation loss consider only vertical maneuvers. The aircraft must follow defined routes in the airport traffic zone, and horizontal maneuvers could potentially cause path violations. The action description indicates for both aircraft involved (the target aircraft and the aircraft identified by the "other TrackID involved in the event"), what vertical maneuver (if any) they should execute.

Situation where both aircraft have to change altitude in the same direction (up or down) is unrealistic, as the point of corrective action is to increase vertical separation between aircraft, not maintain or decrease it. Therefore such a combination will not be considered.

The corrective action codes are specified in Appendix 5.

4.6 Conclusions

The DSS prototype embodies the norm violation risk model proposed in the previous chapter. It illustrates the modeling of several normative rules for the approaching aircraft, and provides a real-time simulation of the proposed decision support scenario.

Five phases of the decision support process are identified: data fusion, prediction, norm violation evaluation, norm violation visualization and corrective action selection. Each of these phases can be implemented in a number of ways. There are a lot of methods for data fusion, or aircraft position prediction, there are many ways to represent risk indicators, etc. The main focus of this work is representing norms as risk item definitions: showing what subset of norms can be operationalized how to accomplish it, and how to present the results of risk evaluation to the controller. The complete specification of every decision support process phase is out of scope of this work. The DSS prototype implements the full decision support process, so, certain design solutions are adopted in each phase. However, different solutions also exist and their suitability could be the subject of further studies.

Kalman filter is applied to solve two problems – radar and lidar data fusion, and aircraft trajectory prediction. Filter parameter tuning is demonstrated. Corrective action selection is defined, using prescribed actions method.

The results of this chapter were published in (Lapin, Čyras & Savičienė, 2012), (Savičienė, 2009), and (Savičienė, Operationalization of Regulations…, 2011).

5 Modeling and Visualization of Specific Norms

This chapter presents the results of modeling and visualization of specific normative rules. Section 5.1 is dedicated to modeling and visualization of the aircraft approach procedures. Two visualization methods are proposed. Section 5.2 is dedicated to modeling wake turbulence separation, section 5.3 – modeling and visualization of the ash cloud risk. Section 5.4 describes the performed demonstrations of the DSS prototype and analyses applicability of the prototype to the future SESAR models of ATC.

5.1 Modeling and Visualization of the Approach Procedures

5.1.1 The DSS Usage Scenario

The DSS prototype proposes the following usage scenario. The overall situation is presented in 3D view window with generalized landscape and tracks observed by the DSS prototype. This screen imitates the situation that is viewed from the tower but without distracting details. Usually an aircraft can hardly be seen from the tower, whereas the DSS highlights it. The DSS control panel presents the current information about the observed tracks and norm violation risks. A separate 2D window comprises user interface buttons and the message board. Violations are visualized in 3D view using colors and explained in the message board.

The zone can be shown in two observation modes:

- A soft control mode where aircraft altitude and the separation between the detected aircraft is controlled;
- Strict control mode where certain approach/departure procedure is assigned to the primary aircraft, and procedure constraints (altitude, speed, and track) can be followed.

In the soft control mode the horizontal and vertical distances between each pair of the aircraft are calculated. If the distance is less than allowed minimum, a loss of separation risk is identified and the aircraft icon becomes red. In the case that the minimal safe distance is calculated from predicted positions, the risk indicator on the DSS control panel becomes yellow and an appropriate message appears on the message board.

A strict control mode shows the aircraft with respect to the constraints (altitude, speed and track) of the assigned airport procedure. For the approach procedure, it is defined within 6 NM, between the FAF and TP points. The assigned procedure is visualized so that the aircraft position validity can be detected visually and confirmed with colors. The tracked aircraft is depicted in green if it follows the assigned procedure.

After an aircraft receives a clearance for take-off/landing, the DSS scenario comprises the following steps:

1. Assign an approach/departure procedure: the procedure is visualized. Two alternative visualizations have been developed for path violation visualization (see subsections 5.1.2 and 5.1.3).
2. Observe the situation.
3. Issue instructions for the pilot.

A path violation is detected in 3D view or color indicators on the message board. The path and separation violation risks are shown with colors: green, yellow and red. The numerical value is shown above the indicator.

5.1.2 2D-in-3D Prototype

This prototype combines ideas of 2D walls for approach control and stack control (Fig. 21). Approach procedures present trajectory constraints in a profile view; see an example in Fig. 60. This view is convenient for aviation professionals. The constraints are presented in alphanumeric texts. The constraints can be projected in the 2D wall. Thus, display cluttering is reduced.

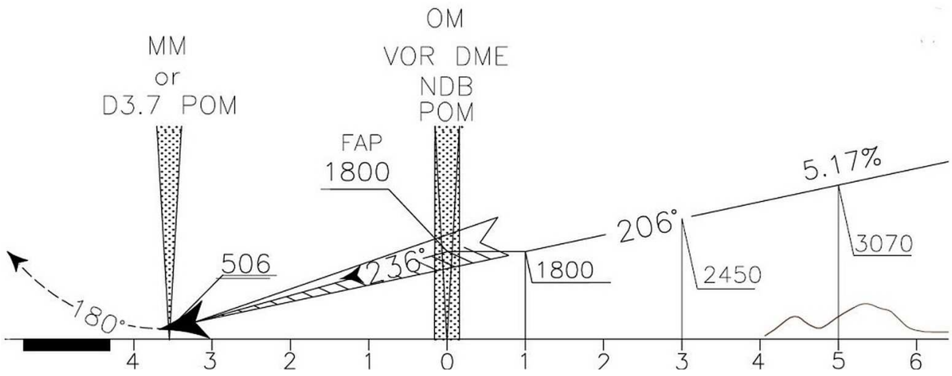

Figure 60. Example profile view of an approach chart (VATITA, 2003)

In 2D-in-3D prototype, the 2D wall for approach control is enhanced with semitransparent curtains. The walls cover a significant area of the screen. They also hide a context view behind and underneath them. Semitransparent curtains are a solution to avoid the hiding.

An airport zone is divided into two vertical spaces. The space below a determined altitude (transitional altitude) is allowed for an aircraft which obtained a landing clearance. With regard to this space, the approach and departure procedures are visualized.

The space above a determined altitude is devoted to aircraft which approach the airport from outside. In this space, the task of the controller is to ensure appropriate horizontal and vertical separations. Therefore, the altitude rulers can be integrated with vertical curtains. The number of rulers depends on waiting loops determined in a concrete airport. The rulers enable the controller to monitor a holding stack of landing aircraft.

2D-in-3D prototype utilizes a generalized terrain representation (Fig. 61, the airport is a white icon in the center; small white indicators depict two aircraft). Important terrain peculiarities comprise sea line and high objects such as mountains. The 3D terrain presentation is helpful for orientation; it improves intuitiveness and does not clutter the display.

Opaque walls can be replaced with transparent curtains. This enables a transparent view. The surroundings are seen like through a curtain. Transition height is represented with a different color – like in the Wall View with

Altitude Rulers (Fig. 21). A trajectory is represented with projection lines on the curtains. White indicators show exact position of the aircraft (Fig. 62).

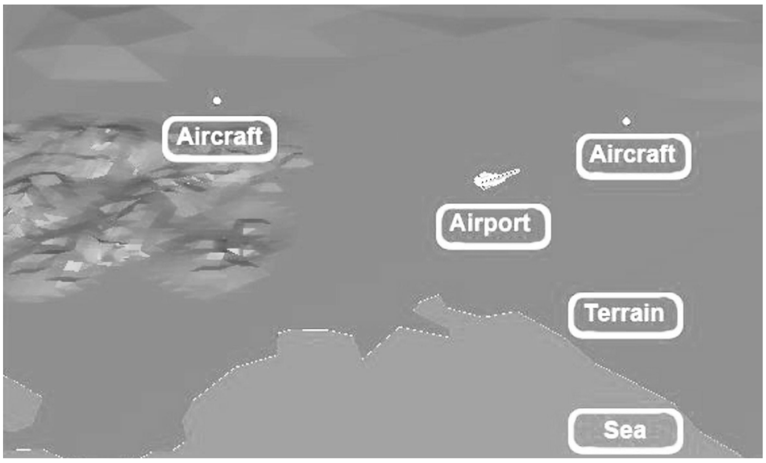

Figure 61. Generalized terrain model

Other features of this model (Fig. 62) are the following:

- FAF is visualized for the procedure; notice dashed lines.
- The approach trajectory is rotated about 90 degrees. Thus, the “back” curtain is clearly seen. The profile view of the procedure which is parallel to the runway is represented on the “back” curtain.
- The approach trajectory is not shown, only the projections of the aircraft position. The reason is that due to the selected viewing angle a representation would be imprecise and bring little information.

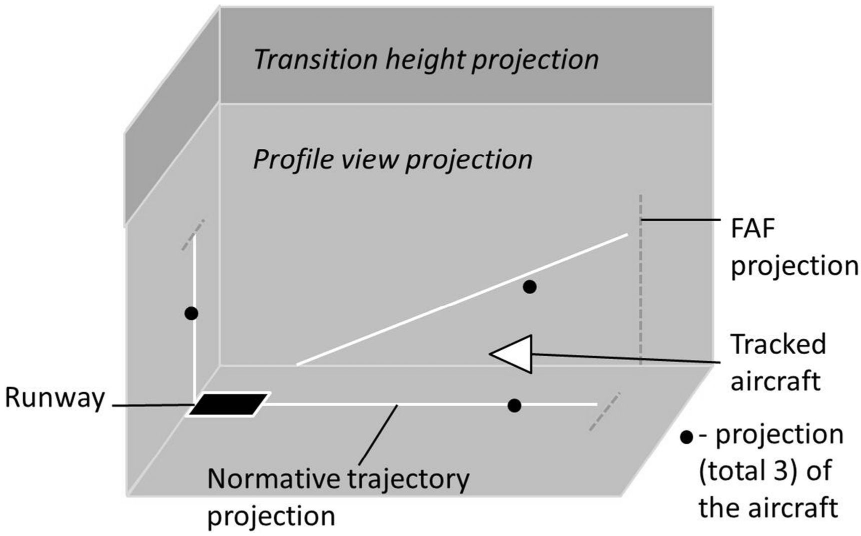

Figure 62. 2D-in-3D visualization model

If the aircraft projection is not on the trajectory projection line, there is a path violation. Approach procedure violations can be tracked in the real time (Fig. 63). The white lines present the projections of the approach procedure. The blue lines present the projections of the main approach milestone, the FAF fly-over point. The green indicator depicts a tracked aircraft. Two black indicators show the projections of the actual position.

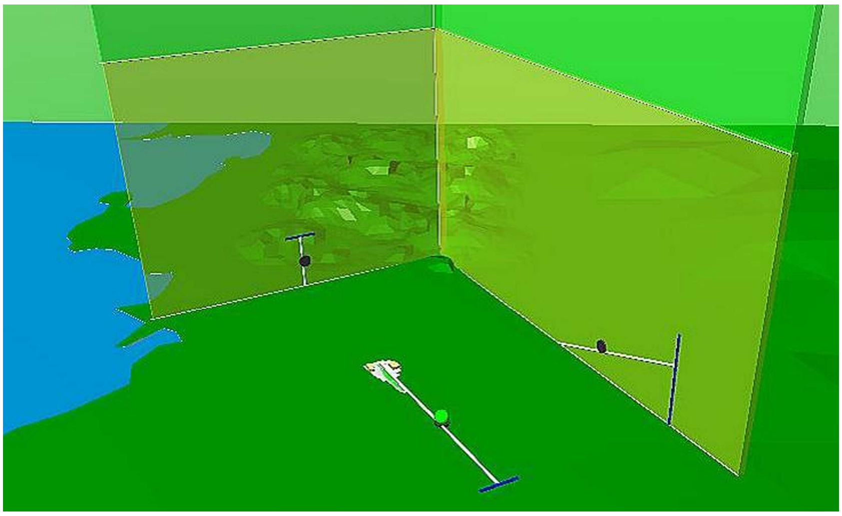

Figure 63. Approach procedure tracking in 2D-in-3D prototype

5.1.3 Pure 3D Prototype

For an alternative prototype a pure 3D approach is chosen. It shows the actual aircraft position, airport terrain and the “tunnel” of the approach procedure (Fig. 64).

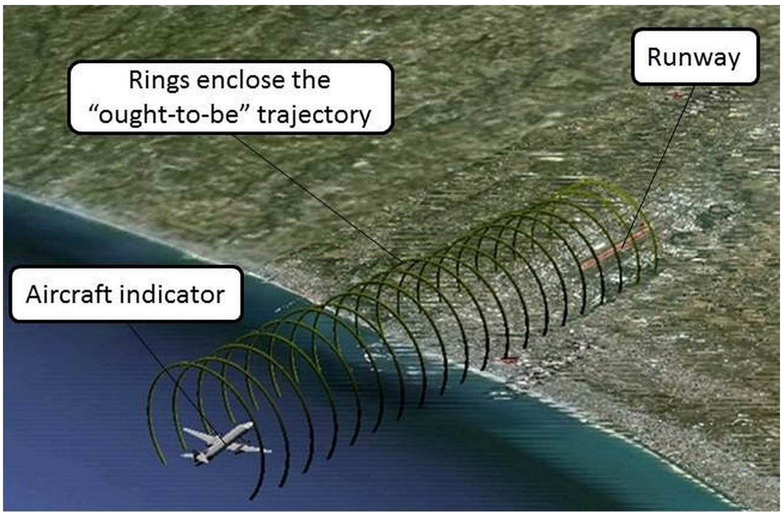

Figure 64. Pure 3D visualization model

A map made of satellite photographs serves as the airport terrain (Fig. 65). The airport and its nearest surroundings are depicted with higher resolution pictures, and lower resolution pictures are used for the rest of the area. On one hand this terrain is more realistic than the generalized terrain in the previous prototype. On the other hand the elevation is shown only with color, but not visualized as 3D model. A realistic 3D icon of the aircraft is used in this prototype. For better visibility the icon is enlarged.

The normative trajectory (the "ought-to-be" trajectory defined in the procedure) is enclosed in wireframe rings. The rings start at the FAF, and for a sort of a tunnel to the runway. The size of rings reflects defined allowable deviation (threshold for detecting possible violation risk). If the aircraft indicator is outside the rings – there is a path violation.

Figure 65. Demonstration of the terrain in pure 3D prototype

A decision support scenario is analogous to the scenario of the first prototype. When a procedure is assigned to the tracked aircraft, procedure rings appear. An aircraft position within the rings indicates that the airport procedure is adhered to (Fig. 66). This visualization model is less strict than the one in 2D-in-3D prototype. However, it is sufficient to assess the trajectory. Horizontal and vertical distances between aircraft are calculated; collision risk is shown with colors.

Both visualization models allow to visually estimate path violation. This eliminates the need to interpret information shown on the control panel and improves situational awareness.

Figure 66. Demonstration of the correct aircraft landing in pure 3D prototype

5.2 Modeling of Wake Turbulence Risk

In order to demonstrate the proposed norm violation risk model, wake turbulence risk is considered. This section deals with the time-based turbulence separation norm (for example, 120 seconds). Time-based separation evaluation involves predicting movement of the aircraft that follows the leading aircraft. The time to reach the current position of the leading aircraft is evaluated. In general, if this time is smaller than the threshold (norm plus allowable deviation), there is a risk. This approach has two drawbacks. First, further into the future the prediction is less reliable. Second, it doesn’t take into account the maneuvers of the leading aircraft. So, in order to represent these rules in the DSS, some sort of turbulence model is needed.

5.2.1 Wake Area Model

A simplified wake turbulence model (Fig. 67) is created, employing ideas from NEXTOR (Shortle et al., 2010).

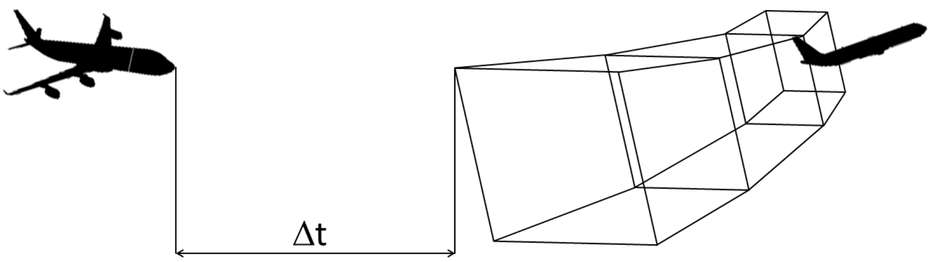

Figure 67. Time-based separation using wake area model

It is a fixed wake area model, composed of polyhedrons. Polyhedrons are defined using only leading aircraft's past positions for the time interval defined in the norm (120 seconds). The interval is divided into several sub-intervals, and a polyhedron is calculated for each sub-interval. The polyhedrons are larger further into the past. These polyhedrons define the area where it is likely to encounter the wake turbulence. The risk evaluation estimates the time Δt it takes another aircraft to reach the wake area defined by polyhedrons. This approach takes into account the maneuvers the leading aircraft has done, and uses shorter predictions (seconds, rather than tens of seconds). These polyhedrons define the area (the wake area) where it is likely to encounter the wake turbulence.

5.2.2 Wake Turbulence Separation Risk Item Definition

In this example nine risk levels (L = 9) are defined: 'no-risk', 'W0', 'G1', 'G2', 'Y3', 'Y4', 'Y5', 'R6' and 'R7' (maximum risk). There are eight (L-1) thresholds: v_0 (threshold for signaling possible violation risk), v_1, v_2, …, v_7 (threshold for signaling maximum risk). The thresholds can be expressed in terms of deviations from the normative value v_N: $v_0 = v_N + \Delta_0$, $v_1 = v_N + \Delta_1$, etc. The Δ_i correspond to the time needed to reach the wake area, Δt. The value used in risk estimation is $v_N + \Delta t$. Consider Δ_4 which is 6 seconds (Fig. 68). If the aircraft is predicted to reach the wake area in 6 seconds or less (but not less than 4 seconds, Δ_5), for example $\Delta t = 5$ seconds, than the risk level is 'Y4'.

Segments of the ranking function, representing risk levels are:

- 'no-risk': $>v_0$, or $\Delta t > \Delta_0$;
- 'W0': $[v_1, v_0]$, or $\Delta t \in [\Delta_1, \Delta_0]$;
- 'G1': $[v_1, v_2]$, or $\Delta t \in [\Delta_2, \Delta_1]$;
- …
- 'R7': $[0, v_7]$, or $\Delta t = 0$.

The corresponding risk item definition is: (1) norm factor: 'time-based turbulence separation'; (2) predicate: '$\geq v_N$'; (3) expected value: 120 s; (4) type:

‘limit’; (5) thresholds: $v_7 = v_N = 120$ s, $v_6 = 122$ s, $v_5 = 124$ s, $v_4 = 126$ s, $v_3 = 128$ s, $v_2 = 130$ s, $v_1 = 132$ s, $v_0 = 134$ s.

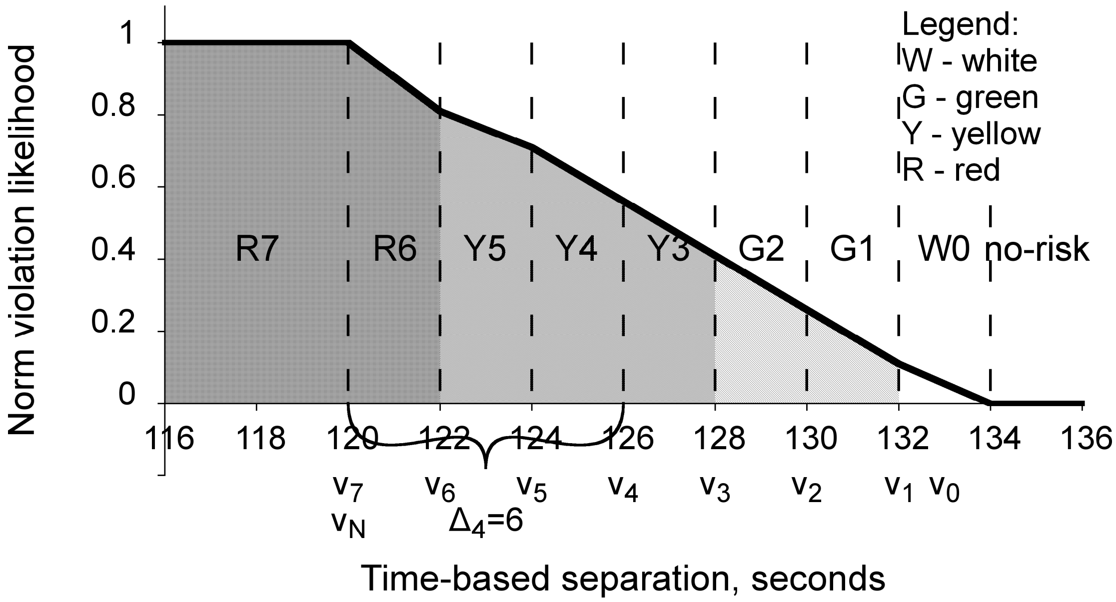

Figure 68. Time-based turbulence separation norm violation modeling

5.3 Modeling and Visualization of Ash Cloud Risk

In this section, it is examined how to expand the proposed decision support model to take into account volcanic ash cloud data and how to transform it into the decision support system.

Diagnostics of volcanic ash clouds deals with small particles in atmosphere. Currently it is not known whether the laser optical diagnostics of volcanic ash clouds using the lidar are possible. This is subject to further research. The lidar system, considered in this work, has a range of 6 NM around the ATZ barycenter. An early warning system for volcanic ash clouds should have a longer range. If the ash cloud is detected when it is 6 NM away from the airport, it could reach the runway in a matter of minutes. In such case the DSS would only indicate the maximum risk.

If the DSS could get the data from distributed lidars across Europe, which would specify the presence or absence of the volcanic ashes at these points, it could be the basis for automated volcanic ash cloud prediction.

The main issue in the volcanic ash cloud modeling is that the DSS is intended to track the aircraft in the ATZ (approximately 6 NM radius), and the volcanic ash cloud is big, much larger than the ATZ. Therefore, when the cloud moves onto the ATZ, it will be fully covered. The modeling is problematic. A series of geometric simplifications is proposed in order to demonstrate volcanic ash cloud risk in the DSS.

5.3.1 Geometric Simplifications

Volcanic ash cloud will be modeled only geometrically and as simply as possible. Each simplification is represented as an assumption in the DSS.

DSS will visualize the cloud movement. There will be no modeling of ash concentration. The “no-fly zone” (the cloud) will be considered where the ash concentration is greater than $4 \times 10^{-3} g/m^3$ limit. It means that flying through the cloud (including take-off and landing) is prohibited.

Assumptions:

1) Ash cloud is the area of particle density > $4 \times 10^{-3} g/m^3$, i.e. no-fly zone. It is a recommended concentration norm in some countries (UK CAA, 2011).

2) Ash cloud is modeled with 60 NM buffer zone – 60 NM is added to the no-fly zone. It is an ICAO ruling (ICAO Eur Doc 019, 2010).

3) Ash cloud is considered to be of infinite height (i.e. only horizontal coordinates of the cloud are considered). For convenience, the 3D model of the cloud will have a defined height (h_{cloud}). This 3D representation of the cloud should be of sufficient height to cover the aircraft trajectories, that are tracked in the DSS (i.e. $h_{cloud} >> h_{transition}$).

4) Ash cloud is a single point. Together with a buffer zone it is modeled as a 3D cylinder of 60 NM radius (Fig. 69).

5) The originating point of the cloud is known. The DSS receives the originating coordinates of this point as input.

6) The cloud moves at a constant (known) speed and at a known direction (angle/bearing) towards the aerodrome. DSS receives cloud speed and direction (bearing) as input.

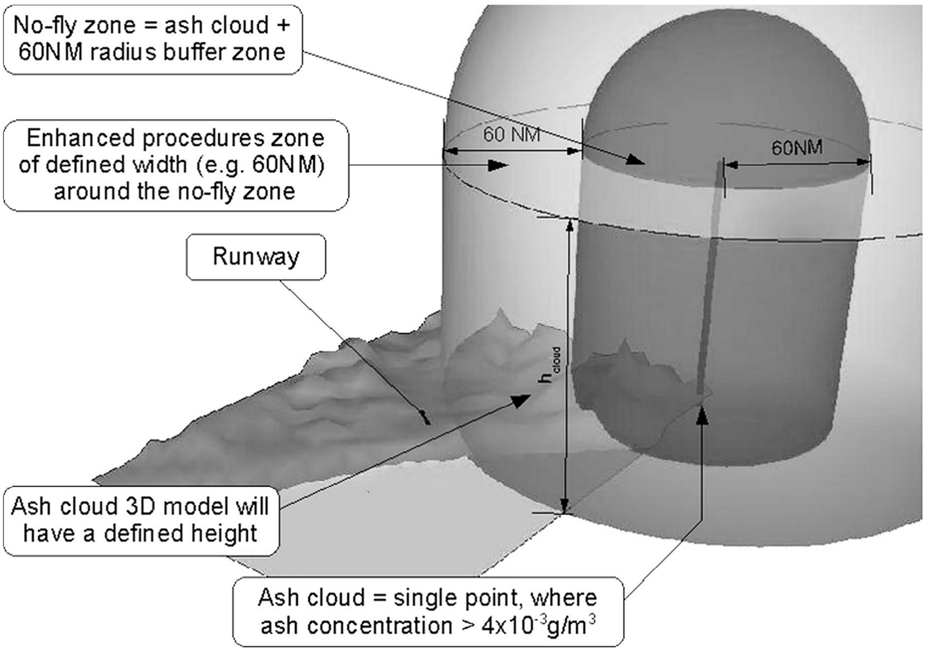

Figure 69. Geometric representation of the volcanic ash cloud

5.3.2 *Volcanic Ash Risk Item Definition*

The DSS does not have volcanic ash concentration data, so risk evaluation cannot be based on the concentration. It will be based on the distance between the aircraft position, and the ash cloud position (known position where the concentration exceeds the norm). The normative rule is interpreted in this way: the aircraft should not enter the zone of high ash concentration. There are several ways to define risk of entering the volcanic ash cloud:

- Conservative risk item definition. The risk is 1 (maximum risk) when in the no-fly zone (area of high concentration plus the buffer zone). Additional area (equivalent to the enhanced procedure zone, EPZ) is added to the no-fly zone. Inside the EPZ, the risk gradually decreases when further away from the cloud and closer to the EPZ outer edge. The risk outside the EPZ is zero (Fig. 70, left).

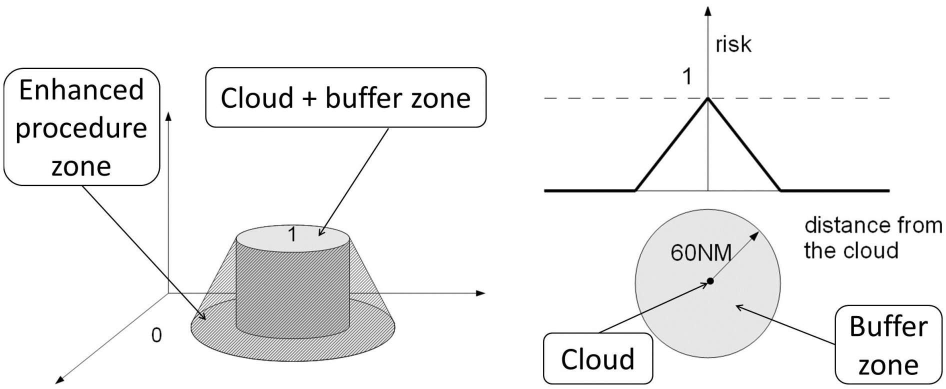

Figure 70. Conservative (left) and less conservative (right) definition of the ash-cloud risk

- Another approach could be less strict. As the BZ was subsequently dropped by the civil aviation authorities, as the area is not considered risky, the risk is 1 only when the aircraft is inside the cloud itself, the risk gradually decreases when further away from the cloud and closer to the outer edge of the BZ. The risk outside BZ is zero (Fig. 70, right).

Ranking function for the strict approach (Fig. 71) is defined in the following way. There are three risk levels (L = 3): ‘green’, ‘yellow’, and ‘red’. In this case the normative value is zero v_N=0: the distance to the ash cloud should be greater than zero (the aircraft has to be outside the cloud). There are two (L-1) thresholds: v_{low} (threshold for signaling possible violation risk – the EPZ) and v_{high} (threshold for signaling maximum risk – the BZ). The thresholds can be expressed in terms of deviations from the normative value v_N: $v_{high} = v_N + \Delta_{high}$, $v_{low} = v_N + \Delta_{low}$.

Segments of the ranking function, representing risk levels are:

- ‘green’: $>v_{low}$;
- ‘yellow’: $[v_{high}, v_{low}]$;
- ‘red’: $<v_{high}$.

The corresponding risk item definition is: (1) norm factor: ‘distance to the position of the volcanic ash cloud (area with ash concentrations above 4×10^{-3}g/m^3)’; (2) predicate: ‘$\geq v_N$’; (3) expected value: 0 NM; (4) type: ‘limit’; (5) thresholds: v_{high} = 60 NM, v_{low} = 120 NM.

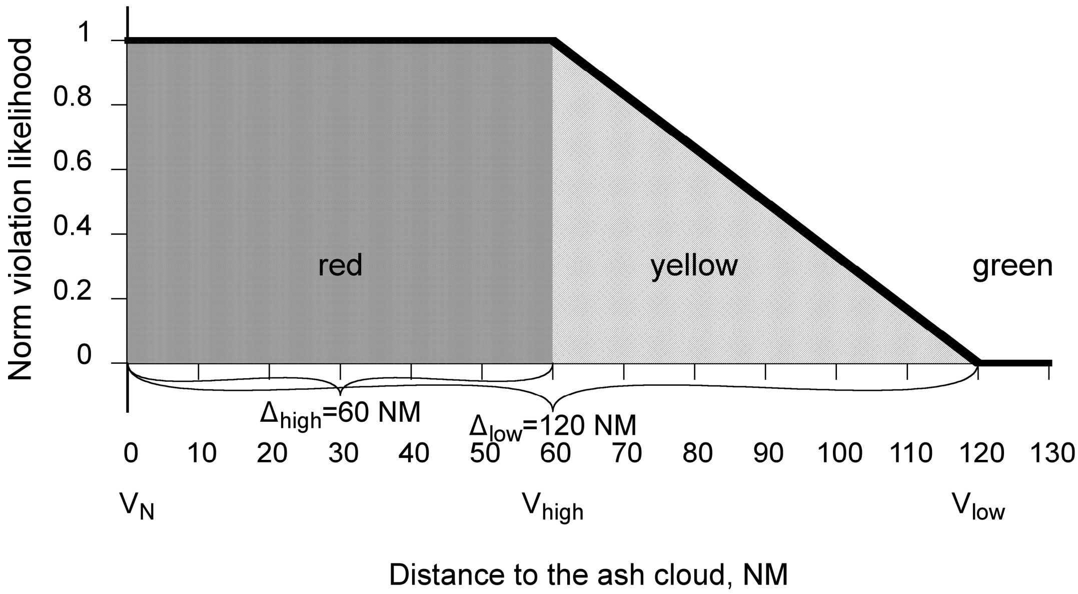

Figure 71. Distance to the ash cloud modeling

5.3.3 Visualization of the Ash Cloud

In the following example (Fig. 72) the cloud is modeled as a single point, where the ash concentration exceeds the high contamination limit. The buffer zone (60 NM radius) is added to the cloud, and together they form a no-fly zone. In this zone the risk for aircraft is 1 (maximum risk, red risk level). A 120 NM wide enhanced procedures zone is added to the buffer zone. In this zone the risk for aircraft is in the interval (0, 1) (yellow risk level). The no-fly zone and the enhanced procedures zone are represented as transparent cylinders (Fig. 73).

Figure 72. Volcanic ash cloud modeling

If the DSS has the data about the movement of the ash cloud, it can visualize the cloud movement. In this simplified case the cloud starting point, direction and speed are entered into the DSS and it shows the no-fly zone and the enhanced procedures zone. The top view (Fig. 73, left) shows the exact position of the zones with respect to the airport area. The side view (Fig. 73, right) shows the approaching cylinder, allowing to visually estimate if the observed aircraft enter the zone.

Figure 73. Volcanic ash no-fly zone and the EPZ represented as cylinders

5.4 Result Demonstration and Validation

The approach/departure DSS prototype is assessed with scientific literature. The findings of the DSS demonstration are of qualitative nature. The demonstration was not intended to measure the performance. Instead, recommendations for future developments are expressed.

5.4.1 Simulation with Radar Data

The prototype was tested using sample day radar data from Napoli/ Capodichino airport. The radar data was from normal flights, without violations that could be considered dangerous. So, the risk thresholds in the DSS were intentionally set to such values that flights would show some risks. The prototype reads the track data from input file every second and calculates risks in real time. The results showed that some flights deviate from the path defined in the procedure (Fig. 75). This shows that additional research is needed to establish what deviations are to be considered normal.

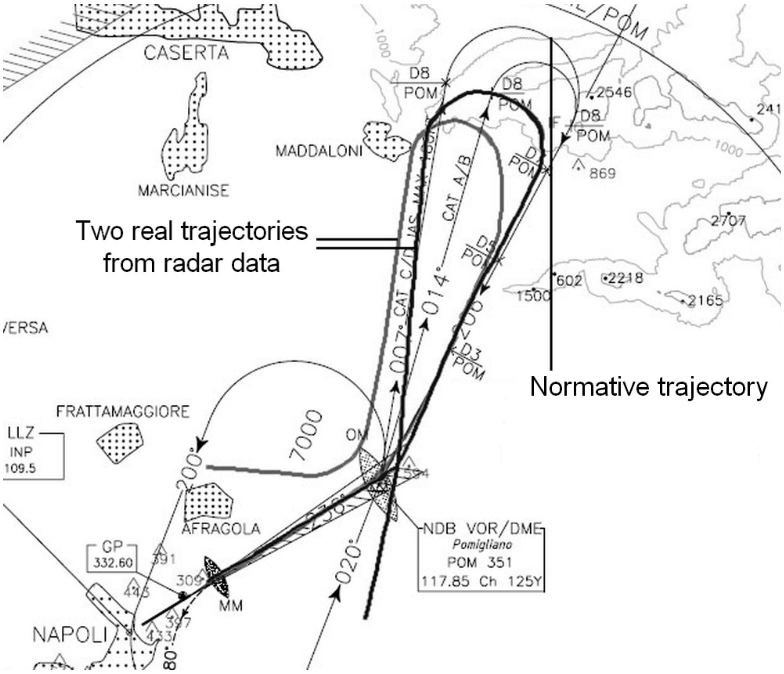

Figure 74. Example of deviations on Napoli ILS-V procedure chart (VATITA, 2003, char no. 353)

5.4.2 Demonstrations

To demonstrate the proposed norm violation risk model, the several norms were modeled and implemented in the prototype system (aircraft separation, approach procedures, wake turbulence separation and ash clouds).

GUI evaluation. The visualization alternatives have been also demonstrated to the controllers from the Pescara airport. The feedback highlighted that a combined 2D-in-3D visualization is more intuitive and contributes to a better decision support. Generalized terrain has been preferred to photographic one. Details on the photographic terrain have been asserted as distracting and disturbing the observation. Violations have been more distinguishable on the curtains than on the wireframe rings.

A message board with indicators has been evaluated as useful and non-distracting. When the main window indicates a violation, complementary data on the message board presents what exactly is violated. In a normal situation there is no need to watch the message board. The decision support scenario was judged as realistic and effective while tracking aircraft in the ATZ.

A comparison of two prototypes shows that the 2D-in-3D prototype may improve situational awareness. A generalized airport environment depicted with essential terrain obstacles provides sufficient orientation in the environment and avoids clutter. 3D curtains with projections of an airport procedure reduce cognitive workload of controllers. This enables to estimate the compliance to approach/departure procedures.

Demonstration to Lithuanian controllers. The approach/departure DSS can be demonstrated as a standalone system simulating with a sample day radar data standing for input. In this way, it has been demonstrated to controllers at three airports in Lithuania. Traffic is not big in each of them, with 10–40 flights per day. All airports are equipped with ILS navigation aids that support the pilot instead of the air traffic controller. The pilot has the responsibility to ensure safe landing and departure. These navigation aids do not require additional tool assistance.

The aircraft which are not equipped with ILS receiver, need precision approach radar (PAR) service. Only one airport in Lithuania provides such a service. The controller who provides the ground approach service stated two positive comments. Firstly, the current ground approach service is provided in a dark room in order to provide better visibility on the PAR screen. The dark room is more troublesome than the tower environment. Secondly, benefits of the DSS are provided by a screen without background clutter reflections and a possibility to track aircraft at low altitudes. The pilot can be guided until the aircraft touches down whereas on the current PAR screen (Fig. 74), the aircraft icon at low altitudes is melted in the background clutter. Such 2D representations of the older radars could be replaced by the proposed 2D-in-3D visualization.

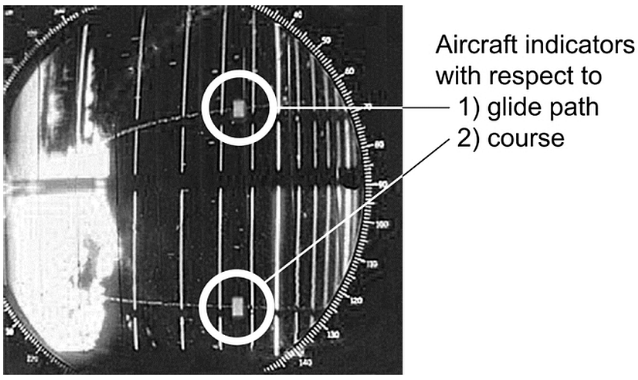

Figure 75. PAR screen; the big lurid patch on the left indicates a background clutter (Forgette, 2007)

5.4.3 Alignment with SESAR Research

As the number of aircraft flights increases, new means to optimize the ATM are sought (Steiner et al., 2008; Gianazza et al., 2009). In Europe, the research in the field of ATM is governed by the SESAR – the Single European Sky ATM Research Programme[4].

4D trajectories. One of the central ideas in the SESAR ATM target concept is the 4D trajectories (SESAR, 2007, p. 18). 4D trajectory is a precise description of the aircraft flight path as a 4-dimensional continuum: each point defined by longitude, latitude, level and time (Wilson, 2007; Eurocontrol, 2008). The planned transition to 4D-trajectory-based operations entails the increased use of fine-grained constraints for aircraft trajectories. Satisfying these constraints is more difficult than in the current mode of operations and requires closer coordination between the pilot and the controller (Zeghal & Dowling, 2008). Therefore, the controllers will need decision support tools to check the trajectory adherence.

Modeling 4D trajectories in the DSS. The 4D trajectory model fits into the perception of geometrical norms in the approach/departure DSS. Trajectory constraints can be defined as four parameters: three coordinates and time. Time in 4D trajectory definition is absolute, specifying exact moment when the aircraft must be in the specified position. The current DSS prototypes so far

[4] http://www.sesarju.eu

incorporate only relative time, e.g. time to reach the TP from FAF, or time-based wake turbulence separation. So, additional work is required to incorporate the absolute time. When this condition is satisfied in the DSS, each 4D trajectory can be expressed as a set of risk item definitions, and the DSS will monitor trajectory adherence.

Support for future aircraft separation modes. In the SESAR target concept, the controller is the default Separator in the Managed airspace (SESAR, 2007, p. 20). Table 13 lists possible DSS support for SESAR separation modes.

Table 13. The approach/departure DSS and SESAR separation modes

Separation mode	**Possible DSS support**
Conventional modes	Situation monitoring and conflict detection
New ground based modes	Situation monitoring and conflict detection (if the precision trajectory clearances are expressed as risk item definitions)
New modes	No direct support

Measurement equipment. SESAR target concept relies on the assumption that new surveillance systems, e.g. ADS-B (Automatic Dependent Surveillance-Broadcast), will increasingly provide improved 4D-trajectory information – position and time (SESAR, 2007, p. 11). ADS-B is a surveillance technology based on GPS navigation and a data link. It is foreseen to become the primary means of surveillance in aviation domain. The DSS is based on a similar assumption – that the precise position data is received from radar and lidar data fusion. But the proposed model does not depend on the data source. Other precise trajectory data sources, including ADS-B, could be used with the same norm violation risk model.

5.5 Conclusions

Specific normative rules for aircraft approach and departure have been modeled in a prototype decision support system: approach procedure constraints (height, horizontal position, glide path), wake turbulence separation, separation from ash clouds. Two visualization models for path violation (violation of the approach procedure) were proposed: integrated 2D-in-3D and pure 3D. They differ on how the procedure constraints are represented. The visualization prototypes provide laboratory implementation, which elaborates technology readiness level 1 and 2 (Mankins, 1995) ideas from other projects to the level 3 – implements them in the practical context defined by requirements for approach/departure DSS.

The results of this chapter were published in (Lapin, Čyras & Savičienė, 2012), (Lapin, Čyras & Savičienė, 2011), (Savičienė, 2009), (Savičienė, Operationalization of Regulations…, 2011), (Savičienė, 2010), and (Savičienė, 2012).

6 Results, Conclusions and Open Issues

6.1 Results

1. A method to model aircraft approach/departure normative rules and visualize violation risk is proposed.
   1.1. Normative rule is modeled as a triplet: factor, normative value, and a predicate. Two norm types are identified: limit-based and deviation-based.
   1.2. Notion of norm violation risk likelihood is defined. Likelihood is understood as a ranking, expressed in the scale from 0 to 1.
   1.3. Risk item definition associates the modeled norm with a set of thresholds and discrete risk levels. Risk evaluation maps the observed value of the factor to a discrete risk level.
2. Normative rules that can be modeled in the approach/departure decision support are identified. The selection includes norms concerning aircraft position and speed. They are referred as "geometrical norms".
3. Proposed risk visualization model and two visualization models for "ought-to-be" trajectory violation (path violation).
   3.1. Each risk level is mapped to one of traffic light colors, to help guide the air traffic controller decisions. Color white is added to the traffic-light colors (red, yellow, and green) to signify risks that are not relevant at the moment. Color of the evaluated risk level is shown in an indicator. Currently each norm results in a separate indicator.
   3.2. Path violation is visualized in the main airspace view. Additional objects (projection curtains in "2D-in-3D" model, and wireframe rings in "pure 3D" model) which are integrated into the main 3D window allow the user to visually estimate compliance with the procedure.

4. A prototype decision support system developed, and several specific norms modeled as a demonstration.
    4.1. The results of the research are validated by experimental system.
    4.2. The prototype DSS provides a real-time simulation and visualization of the air traffic around an airport.
    4.3. The following norm factors are modeled: horizontal and vertical separation, approach/departure procedure vertical profile, indicated airspeed, glide-path, distance to the ash cloud and time-based wake turbulence separation.
5. Participation in the SKY-Scanner project is understood as validation (approbation) of the proposed method.

6.2 Conclusions

1. Modeling and visualization of normative rule violation is possible in the selected application domain – decision support for aircraft approach and departure. Violation model is based on the assumption that precise aircraft position data is available from the surveillance equipment. The proposed model combines simple models: piecewise linear risk function and traffic light model.
2. The proposed method enables to represent selection of aircraft approach/departure normative rules in a decision support system (DSS) for the air traffic controller. These norms are referred as “geometrical norms”.
3. The prototype DSS demonstrates feasibility of the proposed method implementation. The following norm factors are modeled in the prototype DSS: horizontal and vertical separation, approach/departure procedure vertical profile, indicated airspeed, glide-path and time-based wake turbulence separation.
4. Two visualization models for path violation are proposed: (1) “2D-in-3D” and (2) “Pure 3D”. They differ on how the aircraft trajectory adherence to

the airport procedures is visualized (on projection curtains or with wireframe rings).

5. The norm violation risk modeling can be automated for the factors demonstrated in the prototype DSS. To model other factors additional analysis is needed.

6.3 Open Issues

This section is an overview of open issues and questions not considered in the norm violation risk model and/or the DSS prototype.

Conceptual difference of the two risk types. The proposed model contains two risk types: limit-based and deviation based. However, mathematically, the deviation-based risk could be interpreted as a sum of two limit-based risks: ‘$=v_N$’ = ‘$\geq v_N$’ + ‘$\leq v_N$’. The motivation for not following this logic, is the aim to create a simple model, staying close to the application domain. Additional levels of abstraction make it harder for the users to understand the relationship between real-world and model entities, and discourage trusting the system. In this case, transparency is chosen over formal integrity. The author argues that it is important to retain the two types in the risk model level. The implementation level, on the other hand, could employ such limit-based interpretation.

Approach/departure DSS as legal machine. The DSS is designed to facilitate controllers. But imagine it operating autonomously from the controller. This can be compared with airborne collision avoidance system (ACAS) and the pilot. Autonomous means acting as a “legal machine”. Examples of legal machines in other domains are traffic lights, automatic full barriers, etc. On the contrary, road radars support police officers who make decisions to punish or not to punish the driver for a speed violation. The status of a supporting decision support system excludes the status of an automatic legal machine. Currently the acts produced by the DSS are raw facts – not legal acts. The acts produced by a legal machine are institutional acts and have legal importance. To become a legal machine, the DSS needs imposition by an ATM authority.

A long way is needed from the proof-of-concept through validation to a commercial implementation. The status of a legal machine could be achieved in this way but this is out of scope of the present research.

Risk aggregation. In the proposed model, violation risk for each norm is represented as a separate indicator. A method to combine these indicators could be employed to further concentrate the information presented to the user. This issue has two aspects: (1) aggregation of the individual risks and (2) aggregation of the current and predicted risks.

Aggregation of individual risks could be formalized as a simple principle, for example "the overall risk level equals the worst risk level of all evaluated individual risks." More complex heuristics, such as prioritizing the norms and giving lesser regard to the lower priority norms' risk levels, would provide little additional benefit, as the same effect could be achieved by tuning the thresholds in the risk item definitions.

The problem of current and predicted risk aggregation is more conceptual. Let's assume the risk level $L_{current}$ is obtained by evaluating the current aircraft position, and the level $L_{predicted}$ is obtained by evaluating the predicted position, extrapolated, for example, 10 seconds into the future. How to integrate the two evaluations? Intuitively, when $L_{predicted} \neq L_{current}$, the aggregated risk level should be equal to $L_{predicted}$, because it indicates that the aircraft is moving closer or further to violating the norm. The case when $L_{predicted} = L_{current}$, indicates some situation stability, so the aggregated risk level could even be reduced. However, the aggregation method used will depend on the accuracy and reliability of predictions.

List of Publications

Articles in Journals

Lapin, K., Čyras, V. & Savičienė, L. (2012). The SKY-Scanner Time-critical Decision Support System for Surveillance and Risk Evaluation During Landing and Take-off. *Journal of Aerospace Operations, 1*(3), 301-314. ISSN 2211-002X

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About the Author

Laura Savičienė graduated from Vilnius University, Faculty of Mathematics and Informatics in 2003, receiving BSc degree in Informatics. In 2005 she received MSc degree Cum Laude in Informatics, Vilnius University. From 2008 to 2012 she was enrolled into a PhD study program (Informatics) at Vilnius University.

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In 2009 L. Savičienė participated in a doctoral summer school in Northern Ireland.

Reziumė

Šio darbo tyrimo objektas yra norminių taisyklių pažeidimo modeliavimas ir vizualizavimas aviacijos dalykinėje srityje. Norminės taisyklės lėktuvų trajektorijoms paimamos iš skrydžio taisyklių, žemėlapių, schemų, oro uostų procedūrų ir kt. Normos pavyzdys: leistis 3 laipsnių kampu su apribojimais (aukščio, geografiniais ir kt.), nurodytais schemoje. Norminės taisyklės modeliuojamos ir vizualizuojamos sprendimų paramos sistemoje (SPS). Sprendimų parama grindžiama galimo norminės taisyklės pažeidimo vertinimu. Sistema skirta oro uosto skrydžių vadovui ir turi veikti realiu laiku. SPS stebi, vertina ir rekomenduoja, o galutinį sprendimą, kokius nurodymus duoti pilotui, priima žmogus – skrydžių vadovas.

Pasiūlytas metodas modeliuoti normines taisykles lėktuvo kilimo/tūpimo fazėse bei vizualizuoti jų pažeidimą. Norminę taisyklė vaizduojama kaip pažeidimo apibrėžimas sprendimų paramos sistemoje. Identifikuoti du normų tipai: susijusios su apribojimais ir susijusios su nukrypimais. Kiekviena norminė taisyklė modeliuojama kaip trejetas: faktorius, norminė reikšmė ir predikatas. Siūloma formalizuoti pažeidimo sąvoką sprendimų paramos sistemos kontekste. Pažeidimo apibrėžimas susieja modeliuojamą norminę taisyklę su slenksčių aibe ir diskrečiais tikėtinumo lygmenimis. Kuriamame prototipe naudojami „šviesoforo“ lygmenys: žalia-geltona-raudona. Pažeidimas vizualizuojamas (pateikiamas suvokimui akimis) spalvotais indikatoriais sistemos valdymo pultelyje. Kitų projektų inovatyvios vizualizavimo idėjos buvo pritaikytos lidaru grindžiamai SPS: pasiūlyti du trajektorijos atitikimo oro uosto procedūroms vizualizavimo modeliai, grįsti trijų dimensijų vaizdais. Juose įvesti papildomi elementai („projekcijų sienos“ ir „žiedai“), palengvinantys vizualų trajektorijos atitikimo normoms įvertinimą.

Appendices

Appendix 1. Examples of Airport Procedures

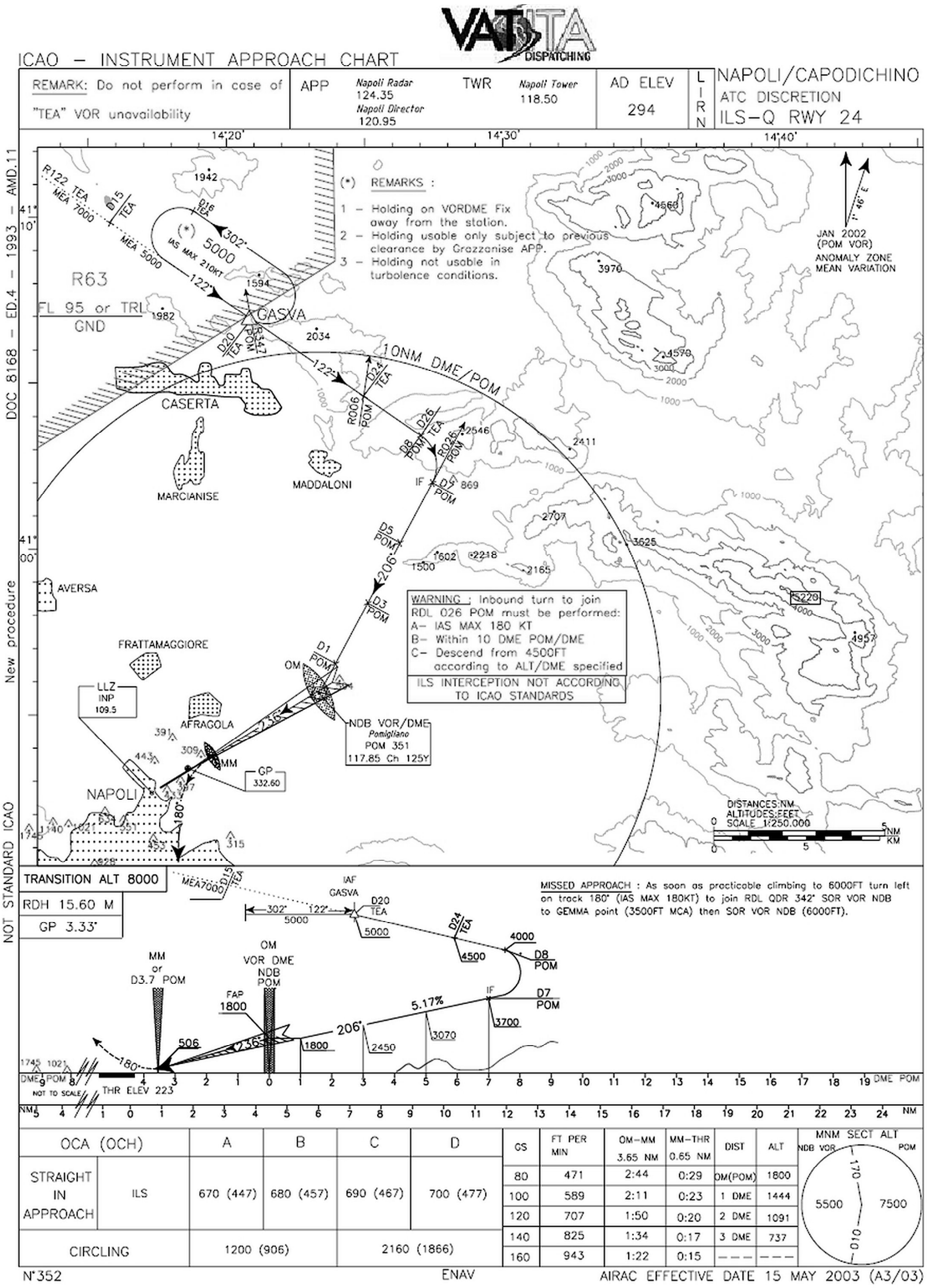

Figure 76. Approach procedure (VATITA, 2003, chart no. 352)

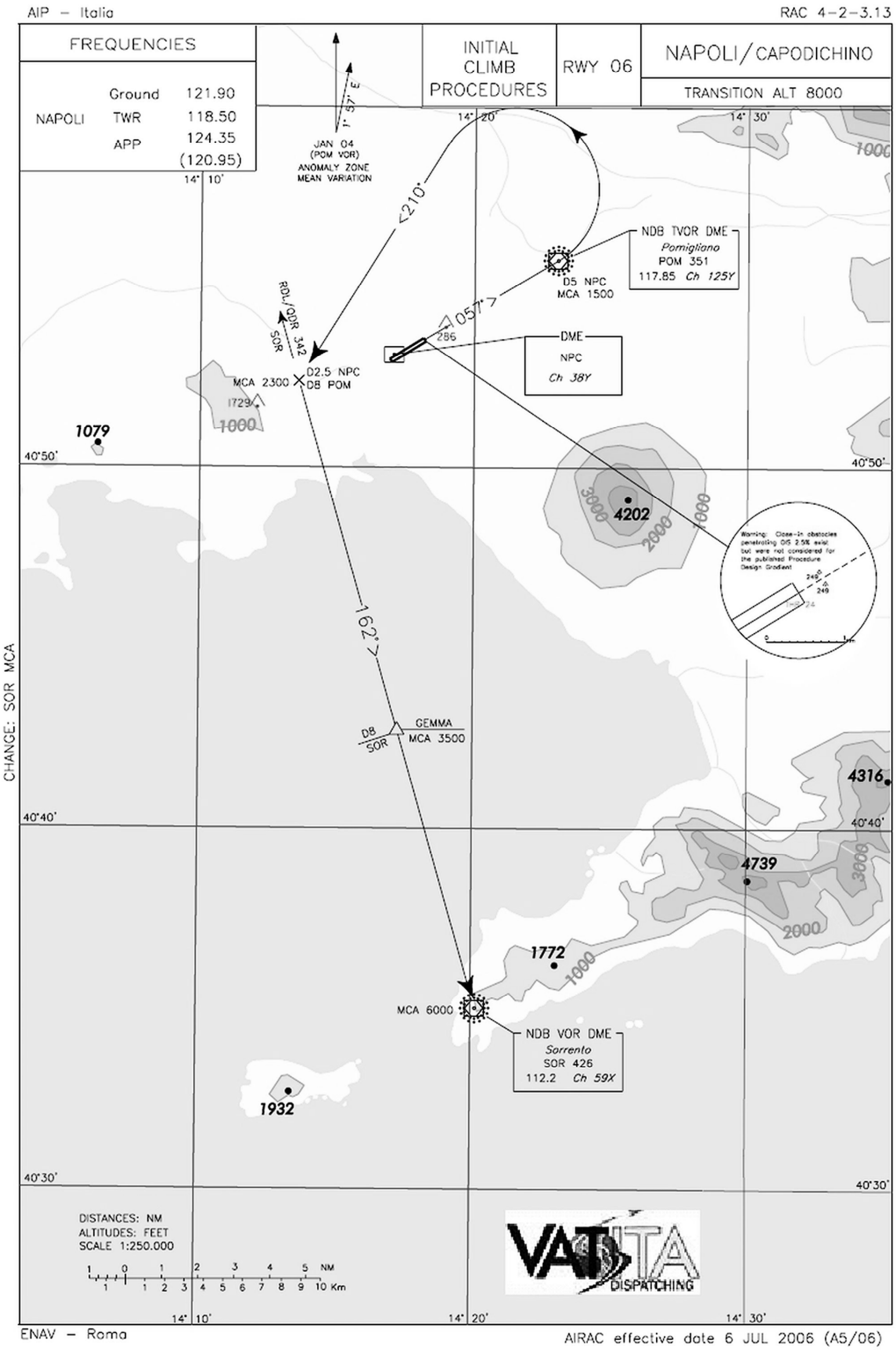

Figure 77. Departure procedure (VATITA, 2003, Initial Climb Procedure Chart)

Initial climb procedure RWY 06

After take-off proceed on track 057° until POM VOR/NDB (D5 NPC DME), to be crossed at 1500 FT or above, then turn left on track 210° until joining RDL/QDR 342 SOR VOR/NDB (TR 162°) bound to point GEMMA then SOR VOR/NDB.
Minimum climb gradient 300 FT/NM until leaving 2300 FT.
Turn speed 230 KT/IAS MAX.

Figure 78. Textual description of the procedure

Appendix 2. DSS Input Protocol

DSS receives the input data through a comma separated value (CSV) file. Each update (set of track data values) is stored in a single line. The CSV file separator is a semicolon (;).

DSS input parameter specification is presented in Table 14. Please note, that “Header” and “Track ID” constitute one CSV field. They are defined separately for clarity. The radar “Track ID” corresponds to the lidar “Track ID” with a “zero” (“0”) that precedes the track number (the information of “Track ID” corresponds to that of progressive track number, a progressive track number is uniquely defined by the C2C for each target in ATZ). This coding will make it possible to distinguish for a target the radar tracks from the lidar tracks.

The transmission of tracks will match with two clusters of possible sensor measure events: (1) new track (track generation) or track refreshment; (2) track cancellation. The transmission of a track cancellation will be identified by the DSS through the control of algebraic sign of track ID. If the sign of the track ID is negative means that the C2C announced the cancellation of a track (target is no longer present in ATZ).

Table 14. DSS input parameter specification

Field #	**Input field**	**Data type**	**Measure-ment unit**	**Remarks**	**Always present in radar tracks?**
1	Header	Character	None	The header equal to “0” means that the track data are from radar. The header different from “0” means that the track data are from lidar systems (see D6, p. 48).	Yes
	Track ID	Integer	None	Progressive number defined by the CSCI-C2 software. Negative Track ID means that the CSCI-C2 announced the cancellation of a track (the target is no longer present in ATZ).	Yes
2	Time	Double	Seconds	Seconds from the first measure of search	Yes
3	Azimuth	Double	Degree in radians	$\in[0, 2\pi)$	Yes

Field #	Input field	Data type	Measure-ment unit	Remarks	Always present in radar tracks?
4	Elevation	Double	Degree in radians	$\in[0, \pi/2]$	Yes
5	Range	Double	Nautical miles		Yes
6	Azimuth Speed	Double	Radians per second		Yes
7	Elevation Speed	Double	Radians per second		Yes
8	Radial Speed	Double	Nautical miles per second		Yes
9	X coordinate	Double	Nautical miles	Coordinates are given with respect to the coordinate centre which is different in each airport. Runway coordinates should be given as a parameter to the DSS for each airport in its “native” coordinate space.	Yes
10	Y coordinate	Double	Nautical miles	See field #9	Yes
11	Z coordinate	Double	Feet	See field #9	Yes
12	Speed along X axis	Double	Nautical miles per second		Yes
13	Speed along Y axis	Double	Nautical miles per second		Yes
14	Speed along Z axis	Double	Feet per second		Yes
15	Last Track Update Time	Double	Seconds	Seconds from the first measure of search	No
16	Track extrapolation indicator	Integer	None		No
17	Track fading number	Integer	None		No
18	Last not extrapolated measure Time	Double	Seconds	Seconds from the first measure of search	No
19	Last not extrapolated	Double	Degree in radians	$\in[0, 2\pi)$	No

Field #	Input field	Data type	Measure-ment unit	Remarks	Always present in radar tracks?
	measure Azimuth				
20	Last not extrapolated measure Elevation	Double	Degree in radians	$\in [0, \pi/2]$	No
21	Last not extrapolated measure Range	Double	Nautical miles		No
22	Last not extrapolated measure Azimuth Speed	Double	Radians per second		No
23	Last not extrapolated measure Elevation Speed	Double	Radians per second		No
24	Last not extrapolated measure Radial Speed	Double	Nautical miles per second		No
25	Last not extrapolated measure X Coordinate	Double	Nautical miles	See field #9	No
26	Last not extrapolated measure Y Coordinate	Double	Nautical miles	See field #9	No
27	Last not extrapolated measure Z Coordinate	Double	Feet	See field #9	No
28	Last not extrapolated measure Speed along X axis	Double	Nautical miles per second		No
29	Last not extrapolated	Double	Nautical miles per		No

Field #	Input field	Data type	Measure-ment unit	Remarks	Always present in radar tracks?
	measure Speed along Y axis		second		
30	Last not extrapolated measure Speed along Z axis	Double	Feet per second		No

Appendix 3. DSS Output Protocol

DSS produces the output data in a comma separated value (CSV) file. There should be one output line for each received track data set. An exception is the track cancellation line (determined by negative track id). There will be no corresponding output for the track cancellation line. Each update (set of track data values) is stored in a single line. The separator in the CSV file is a semicolon (;). DSS output parameter specification is presented in Table 15.

If the DSS performs averaging between radar measure and lidar measure the parameter "Radar – Lidar Data Fusion Flag" will have the value "1". In the cases where the value of the flag is "0" the parameters from the position 2 to the position 6 of Table 15 will be equal to those of the lidar track of origin (lidar measure). If the value of the flag is "1" the parameters from the position 2 to the position 6 of Table 15 will be equal to those averaged between radar measure and lidar measure.

The values that can take N (position 16 of Table 15) are as follows:

- "0" if there isn't a risk of a path violation or a risk of collision with another aircraft;
- "1" if there is a risk of a path violation or a risk of collision with another aircraft;
- "2" if there isn't a risk of a path violation and a risk of collision with another aircraft.

The parameters "Event 1" and "Event 2" will be equal to "0" if "N" is equal to "0".

If "N" is equal to "1" the parameter "Event 1" will be equal to:

- “1” if there is a risk of path violation;
- “2” if there is a risk of collision with another aircraft.

If “N” is equal to “2” the parameter “Event 1” will be equal to “1” and the parameter “Event 2” will be equal to “2”.

The parameters “Airport Actions for the Event 1” and “Airport Actions for the Event 2” include all coded actions that the airport can take to mitigate the possible consequences of the risky events.

Table 15. DSS output parameter specification

Field #	**Output field**	**Data type**	**Measure-ment unit**	**Remarks**
1	Track ID	Integer	None	Equals TrackID from the corresponding input data set
2	Time	Double	Seconds	Equals Time from the corresponding input data set
3	Azimuth	Double	Degree in radians	$\in[0, 2\pi)$
4	Elevation	Double	Degree in radians	$\in[0, \pi /2]$
5	Range	Double	Nautical miles	
6	Azimuth Speed	Double	Radians per second	
7	Elevation Speed	Double	Radians per second	
8	Radial Speed	Double	Nautical miles per second	
9	X Coordinate	Double	Nautical miles	Coordinates are given with respect to the coordinate centre which is different in each airport. Runway coordinates should be given as a parameter to the DSS for each airport in its’ “native” coordinate space.
10	Y Coordinate	Double	Nautical miles	See field #9
11	Z Coordinate	Double	Feet	See field #9
12	Speed along X axis	Double	Nautical miles per second	
13	Speed along Y axis	Double	Nautical miles per	

Field #	Output field	Data type	Measure-ment unit	Remarks
			second	
14	Speed along Z axis	Double	Feet per second	
15	Radar – Lidar Data Fusion Flag	Integer	None	∈[0, 1]
16	Number of Possible Risky Events (N)	Integer	None	∈[0, 2]
17	Event 1	Integer	None	∈[1, 2]
18	Other Track ID involved by Event 1	Integer	None	One of the track ID values that were given in the previous inputs and have not been declared cancelled.
19	Probability of Event 1	Double	None	∈[0, 1], if Event 1 is 1 (path violation) and several path violations exist, the greatest probability is shown
20	Airport Actions for the Event 1	Long	None	
21	Event 2	Integer	None	0 or 2
22	Other Track ID involved by Event 2	Integer	None	One of the track ID values that were given in the previous inputs and have not been declared cancelled.
23	Probability of Event 2	Double	None	∈[0, 1]
24	Airport Actions for the Event 2	Long	None	

The following table (Table 16) summarizes all possible combinations of DSS output parameters in different situations.

Table 16. DSS output parameters in different situations

Output field / Situation	N	Event 1	Other Track ID involved by Event 1	Probability of Event 1	Actions for the Event1	Event 2	Other Track ID involved by Event 2	Probability of Event 2	Actions for the Event2
No risk	0	0	0	0	0	0	0	0	0

Output field / Situation	N	Event 1	Other Track ID involved by Event 1	Probability of Event 1	Actions for the Event1	Event 2	Other Track ID involved by Event 2	Probability of Event 2	Actions for the Event2
Only risk of path violation	1	1	0	∈(0, 1]	L	0	0	0	0
Only risk of collision	1	2	I	∈(0, 1]	L	0	0	0	0
Both risk of path violation and risk of collision	2	1	0	∈(0, 1]	L	2	I	∈(0, 1]	L

Table legend: L – positive long value, I – positive integer value.

Appendix 4. Flight Phase Definitions

The International Civil Aviation Organization (ICAO) and the Commercial Aviation Safety Team (CAST) have recently started an ongoing effort (CAST/ICAO Common Taxonomy Team) to develop common taxonomies and definitions for aviation accident and incident reporting systems. Among others, common taxonomy for the phases of flight is developed; it consists of the following phases and sub-phases (CAST/ICAO CTT, 2011):

1. Standing (STD) – Prior to pushback or taxi, or after arrival, at the gate, ramp, or parking area, while the aircraft is stationary.

    a. Engine(s) not operating

    b. Engine(s) start-up

    c. Engine(s) operating

    d. Engine(s) shutdown: From the start of the shutdown sequence until the engine(s) cease rotation.

2. Pushback/towing (PBT) – Aircraft is moving in the gate, ramp, or parking area, assisted by a tow vehicle (tug).

    a. Assisted, engine(s) not operating

    b. Assisted, engine(s) start-up

c. Assisted, engine(s) operating

d. Assisted, engine(s) shut down

3. Taxi (TXI) – The aircraft is moving on the aerodrome surface under its own power prior to takeoff or after landing.

a. Taxi to runway: Commences when the aircraft begins to move under its own power leaving the gate, ramp, apron, or parking area, and terminates upon reaching the runway.

b. Taxi to takeoff position: From entering the runway until reaching the takeoff position.

c. Taxi from runway: Begins upon exiting the landing runway and terminates upon arrival at the gate, ramp, apron, or parking area, when the aircraft ceases to move under its own power.

4. Takeoff (TOF) – From the application of takeoff power, through rotation and to an altitude of 35 feet above runway elevation.

a. Takeoff. From the application of takeoff power, through rotation and to an altitude of 35 feet above runway elevation or until gear-up selection, whichever comes first.

b. Rejected takeoff. During Takeoff, from the point where the decision to abort has been taken until the aircraft begins to taxi from the runway

5. Initial climb (ICL) – From the end of the Takeoff sub-phase to the first prescribed power reduction, or until reaching 1000 feet above runway elevation or the VFR pattern, whichever comes first.

6. En-route (ENR) – Instrument flight rules (IFR): From completion of Initial Climb through cruise altitude and completion of controlled descent to the Initial Approach Fix (IAF). Visual Flight Rules (VFR): From completion of Initial Climb through cruise and controlled descent to the VFR pattern altitude or 1000 feet above runway elevation, whichever comes first.

a. Climb to cruise: IFR: From completion of Initial Climb to arrival at initial assigned cruise altitude. VFR: From completion of Initial Climb to initial cruise altitude.

b. Cruise: Any level flight segment after arrival at initial cruise altitude until the start of descent to the destination.

c. Change of cruise level: Any climb or descent during cruise after the initial climb to cruise, but before descent to the destination.

d. Descent: IFR: Descent from cruise to either Initial approach fix (IAF) or VFR pattern entry. VFR: Descent from cruise to the VFR pattern entry or 1000 feet above the runway elevation, whichever comes first.

e. Holding: Execution of a predetermined maneuver (usually an oval race track pattern) which keeps the aircraft within a specified airspace while awaiting further clearance. Descent during holding is also covered in this sub-phase.

7. Maneuvering (MNV) – Low altitude/aerobatic flight operations

a. Aerobatics: Any intentional maneuvering that exceeds 30 degrees of pitch attitude or 60 degrees of bank, or both, or abnormal acceleration (usually associated with air shows and military flight, or with related training flights).

b. Low flying: Intentional low-altitude flight not connected with a landing or takeoff, usually in preparation for or during observation work, demonstration, photography work, aerial application, training, sight-seeing, ostentatious display, or other similar activity. For rotorcraft, this also includes hovering (not associated with landing or takeoff) and handling external loads.

8. Approach (APR) – Instrument flight rules (IFR): From the Initial approach fix (IAF) to the beginning of the landing flare. Visual flight rules (VFR): From the point of VFR pattern entry, or 1000 feet above the runway elevation, to the beginning of the landing flare.

a. Initial Approach (IFR): From the IAF to the Final approach fix (FAF).

b. Final Approach (IFR): From the FAF to the beginning of the landing flare.

c. Circuit pattern – downwind (VFR): A flight path (normally 1,000 feet above the runway) which commences abeam the departure end of the runway and runs parallel to the runway in the direction opposite to landing, and terminates upon initiating the turn to base leg.

d. Circuit pattern – base (VFR): From start of turn at end of downwind leg until the start of the turn for final.

e. Circuit pattern - final (VFR): From the start of the turn to intercept the extended runway centerline, normally at the end of base leg, to the beginning of the landing flare. Includes VFR straight-in approaches.

f. Circuit pattern – crosswind (VFR): A flight path of the VFR traffic pattern, which is perpendicular to the landing runway, crosses the departure end of the runway, and connects with the downwind leg.

g. Missed approach/go-around: From the first application of power after the crew elects to execute a missed approach or go-around until the aircraft re-enters the sequence for a VFR pattern (go-around) or until the aircraft reaches the IAF for another approach (IFR)

9. Landing (LDG) – From the beginning of the landing flare until aircraft exits the landing runway, comes to a stop on the runway, or when power is applied for takeoff in the case of a touch-and-go landing.

a. Flare: Transition from nose-low to nose-up attitude just before landing until touchdown.

b. Landing roll: After touchdown until aircraft exits the landing runway or comes to a stop, whichever occurs first.

10. Emergency descent (EMG) – A controlled descent during any airborne phase in response to a perceived emergency situation.

11. Uncontrolled descent (UND) – A descent during any airborne phase in which the aircraft does not sustain controlled flight.

12. Post-impact (PIM) – Any of that portion of the Flight which occurs after impact with a person, object, obstacle or terrain. This phase is added to permit accurate sequence of event reconstruction for occurrences.

13. Unknown (UNK) – Phase of flight is not discernable from the information available.

This list provides unambiguous definitions of what constitutes each phase of flight and facilitates the exchange and comparison of events.

Appendix 5. Risk and Action Codes

Based on the defined limitations, the path violation events may be categorized as follows (on ground, landing and take-off phases are not considered by the DSS):

1. Vertical position violation
   1.1. Altitude violation
   1.2. Glide path violation
   1.3. Obstacle clearance violation
2. Speed violation
   2.1. Climb gradient violation
   2.2. Indicated airspeed violation
3. Position violation
   3.1. Course violation
   3.2. Maneuver area violation
   3.3. Circling sector violation

As some violations may occur at the same time, path violation event code will encode all possible combinations. Path violation event code will be equivalent to the 8-bit number, where each bit represents the existence of certain path violation. For example, code 130 would mean altitude violation and maneuver area violation (see Fig. 78).

Violation number	1.1	1.2	1.3	2.1	2.2	3.1	3.2	3.3
	1	0	0	0	0	0	1	0
Bit number	7	6	5	4	3	2	1	0

Figure 79. Path violation event code construction

So, the loss of separation event will be considered as the penetration of the aircraft protected zone, or volume of airspace surrounding each aircraft that should not be infringed upon by another vehicle, by the other aircraft. The protected zone is defined by ATC separation standards and take-off/landing rules. Penetration may be vertical, horizontal, or both, so the collision events may be classified as follows (collision event code is in brackets – as there are less different loss of reparation risk events than path violation risk events, there is no need for coding scheme):

1. **Vertical separation violation –** the vertical separation is violated (collision event code – 1).
2. **Horizontal separation violation –** the horizontal separation is violated (collision event code –2).
3. **Vertical and horizontal separation violation –** both vertical and horizontal separation is violated (collision event code **–** 3).

Possible actions that can be proposed by the DSS and their codes are listed in Table 17. The Airport Actions value for the output is obtained like this: event code (either path violation or collision) is multiplied by 1000 and action code is added. So, if there is an altitude violation and maneuver area violation, and the DSS proposes for the aircraft to climb, the resulting action is 130111.

Table 17. Corrective action codes

Type	**Action**	**Code**	**Remarks**
Path violation Collision	Do nothing	0	DSS suggests to take no action
Path violation	Initiate missed approach	100	
Path violation Collision	No valid action	999	DSS was unable to select an appropriate action
Path violation	Climb	111	
Path violation	Descend	112	
Path violation	Increase V/S	121	
Path violation	Decrease IAS	122	
Path violation	Turn left	131	
Path violation	Turn right	132	
Collision	Aircraft 1 up	210	Aircraft 1 in this context is the aircraft for which the track is being analysed, and aircraft 2 – aircraft with another TrackID
Collision	Aircraft 1 down	220	
Collision	Aircraft 2 up	201	
Collision	Aircraft 2 down	202	
Collision	Aircraft 1 down, aircraft 1 up	221	
Collision	Aircraft 1 up, aircraft 2 down	212	