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A review of research on risk and safety modelling in civil aviation

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ABSTRACT

Safety is considered as some of the most important operational characteristics of contemporary civil aviation. An extensive regulatory structure has been established to supplement the private airline, airport and air navigation systems, incentives to limit the risks of flying. This paper reviews the research on risk and safety modelling in civil aviation. In such a context, the basic concepts and definitions of risk, safety and their evaluation are described. The review focuses on four categories of models for safety assessment: causal for aircraft and air traffic control/management operations, collision risk, human factor error and third-party risk.

1. Introduction

Air transport is one of the fastest growing modes of transport, and is forecast to grow at an annual rate of between 5% and 6% over the next two decades. Growth rates in international markets are expected to be about twice those in domestic markets, and faster in developing countries. The system's infrastructure—airports and air traffic control/management (ATC/ATM)—has the objective of supporting this growth safely, efficiently and effectively. Air transport, however, is a complex system involving a complicated, interlinking distributed network of human operators, procedures and technical/technological systems. These factors make the provision of a socially acceptable level of safety difficult (Blom et al., 1998; European Commission, 1999). Due to the potentially severe consequences of accidents, safety has always been considered an issue of greatest importance in the sector (Janic, 2000). This paper focuses on the methods and models used for the assessment of risk for individual aircraft and for ATC/ATM operations.

For a long time, the interpretation of safety depended on the system involved and the purpose of the analysis (Kumamoto and Henley, 1996). For technical systems, risk is related to the probability of failure of components or of an entire system causing exposure to hazard and related consequences. In commercial systems, risk is the chance of being exposed to the hazard of losing business opportunities by making inappropriate decisions when there is a known probability of failure. In terms of safety, risk can be considered as a combination of the probability or frequency of occurrence and the magnitude of consequences or severity of a hazardous event (Bahr, 1997).[1]

In air transport, risk has traditionally been related to air traffic accidents resulting in the significant loss of life and property. Assuming that flying is an individual's choice and that the system deploys some resources to satisfy such choice, four types of risks can be identified: risk to an individual, statistical risk of the occurrence of an accident, predicted risk and perceived risk. While these types of risk, albeit with particular nuances, are common across transport modes, air traffic accidents have some distinguishing features. For example, they can occur at any point in time and space because flights are not limited by "roadways" and they are relatively rare events but often have severe consequences. Additionally while the main target groups exposed to the risk are air passengers and crew, "third-party" individuals on the ground may be exposed, but with generally lower probability of losing life or property.

2. Models for assessment of the risk and safety

Fig. 1 offers a generic scheme for analysing air traffic accidents and their consequences (Federal Aviation Administration and European Organization for Safety of Air Navigation, 2005). The first group of models deals with assessment of risk and safety of aircraft operations supported by ATC/ATM and, in particular, with failures of particular technical systems and components that result in an aircraft crash. The failures can be due to many interrelated causes either in the aircraft or at ATC/

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[1] This contrasts, as Frank Knight pointed out over 80 years ago, to uncertainty where there is no calculable probability.

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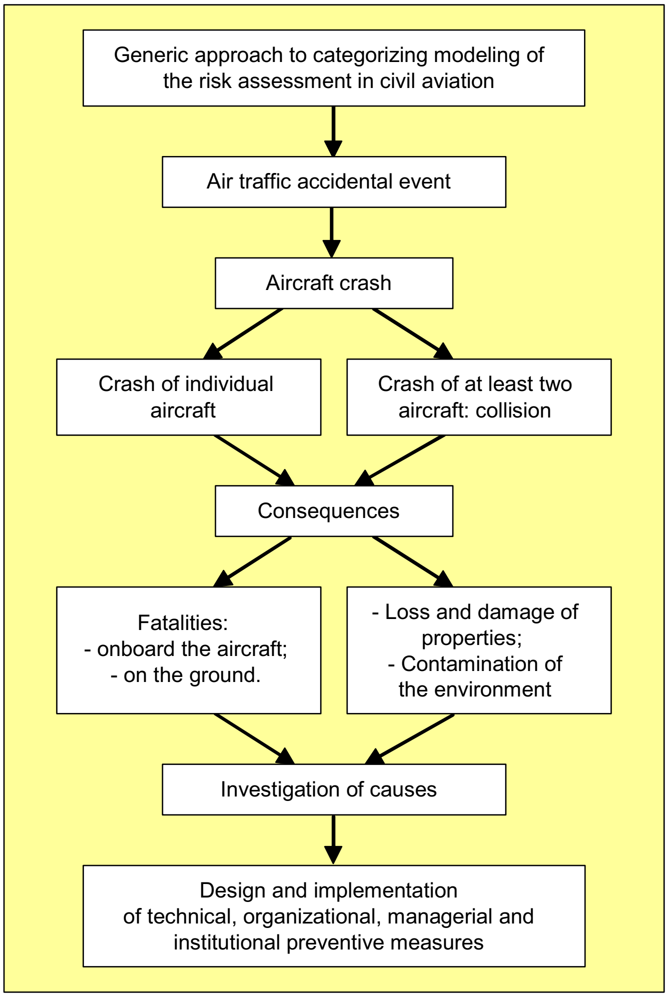
Generic approach to categorizing modeling of the risk assessment in civil aviation
Air traffic accidental event
Aircraft crash
Crash of individual aircraft
Crash of at least two aircraft: collision
Consequences
Fatalities:
- onboard the aircraft;
- on the ground.
- Loss and damage of properties;
- Contamination of the environment
Investigation of causes
Design and implementation of technical, organizational, managerial and institutional preventive measures

Fig. 1. A generic scheme for analysing air traffic accidents and their consequences.

ATM. The second category deals with assessment of the risk of aircraft collision while airborne and/or on the ground due to deterioration of ATC/ATM separation rules. In addition, it embraces methods for assessment of the risk of collision of an aircraft generally with terrain and particularly during missed approach. The third deals with risk and safety assessment of air traffic incidents and accidents due to human error (mostly of ATC/ATM controllers). The final category considers the risk assessment for people on the ground, who might be affected by the aircraft crash.

The categorisation of models is somewhat arbitrary—there are inevitable overlaps and the dividing lines could have been different. There is a focus on proactive modelling approach—i.e., on models that anticipate the problems due to which the accidents occur. In terms of presentation, the approaches are largely examined in the order they were developed.

3. Causal models for risk and safety assessment

Causal models of assessment of risk and safety of aircraft and ATM/ATC operations establish the theoretical framework of causes that might lead to aircraft accidents. They can be qualitative or quantitative, with the former providing a diagrammatic or hierarchical description of the factors that might cause accidents, which is useful for improving understanding of causes of accidents and proposing means for avoiding them. The latter estimate the probability of occurrence of each cause and thus estimate the risk of accident. This can be restricted to pure statistical analysis based on the available data or it can combine such data with expert judgement on causes. In addition, they can estimate the relative benefits of different interventions aimed at preventing accidents (Spouge, 2004). The methods deployed include the following:

- Fault tree analysis (FTA) was developed by Bell Telephone Laboratories (Kumamoto and Henley, 1996) and has been used for analysing events or combinations of events that might lead to a hazard or an event with serious consequences. Usually, it has involved using a fault tree with paths representing different combinations of instant-direct and intermediate causes described by logical operators (“and” and “or”). At the top of the tree is a hazard event or a serious consequence. Then, for a given tree, the minimum cut set is determined—i.e., the minimal set of failures of which if all occur this is followed by the top event. One fault tree might have several minimal cut sets and if only one happens the top event also happens. The probability of occurrence of a given minimum cut set is equivalent to the product of probabilities of occurrence of each event within the set. Consequently, the probability of the occurrence of the top event is the sum of probabilities of particular minimum cut sets. The method has been frequently applied to assess safety, as well as reliability of the aircraft and ATC/ATM computer components.
- Common cause analysis (CCA) is a method for identifying sequences of events leading to an aircraft accident. It is useful to extract the common causes of several aircraft accidents. It “divides” the aircraft into “zones”, implying that the system and components in each zone are ultimately independent. Consequently, it is possible to identify the common causes of failures of particular components of such independent systems. In addition, the method enables identifying and assessing hazard from external causes that might compromise independency between particular systems and components and cause their failures due to the same (common) causes. The US National Aeronautics and Space Administration (NASA) has used this method for a long time (since 1987) although the method itself is probably older than 1975. In addition, it has been recommended for assessment of the risk of failures of aircraft systems and equipment.
- Event tree analysis (ETA) method is used for modelling sequences of events arising from a single hazard and describe the seriousness of the outcomes from these events. ETA was developed in 1980 and is widely used. The hierarchy of presenting a hazard, the sequence of events causing failures of the system components and their state in terms of functioning and failure represent the core of the method. Consequently, a tree with branches of events and functioning and failing components displays probabilities of failures along particular branches. These in combination with the probability of the hazardous event enable quantification of the probability of the system or component failure. This method is applicable in combination with FTA for almost all technical systems including aircraft and ATC/ATM components.
- Bow-Tie analysis presents a combination of ETA and FTA. Origins are from 1970s and 1980s, but since 1999 it has been popularised as a structured approach for risk analysis. The method was recently applied for control flight into terrain (CFIT) accidents (Spouge, 2004). It is complex and incorporates

causal models in the form of fault trees for detecting hazards and estimating the probabilities of related accidents, consequence models in the form of event trees for indicating possible outcomes and their overall risk and safety management models that indicate hierarchically structured measures and interventions aiming at prevention of given categories of accidents. This method could cover a broader range of aircraft accident categories such as: loss of control in flight (LOC) and landing, take-off, ground, structural, fire, mid-air collision, and hostile attack accidents.

- The TOPAZ accident risk assessment methodology uses scenario analysis and a Monte Carlo simulation technique for assessment of the risk and safety of ATC/ATM operations modelled as a Petri nets. It was developed by the Netherlands National Aerospace Laboratory during the 1990s and addresses all types of system safety issues such as technical/technological, organisational, environmental, and human-related and other hazards and their combinations. Risk and safety assessment is performed by identification of the objective; defining operations; identifying the hazard; constructing scenarios; identifying severities; assessing frequency of occurrence; assessing risk tolerability; and identifying the safety bottleneck. These steps can be repeated during the Monte Carlo simulation. Identifying safety bottleneck enables decision-making and specifying the operational requirements in terms of safety for existing and new systems. The method has been applied to risk assessment of ATC/ATM operations: at crossing and converging airport runways, aircraft flying along the parallel tracks en-route, the wake-vortex induced hazard, and continuous descent approach (CDA), mainly around Amsterdam Schiphol airport.
- Bayesian Belief Networks (BBN) is based on probability theory and has been developed to improve understanding of the impacts of different causes of the risk. Originated in the mid-1980s, the method was applied at the beginning of 2000s in the US in the scoping of the aviation system risk model (ASRM) developed by the Federal Aviation Administration (FAA) and the NASA. ASRM has been used to provide a systematic, structured approach for understanding the aircraft accident causality as well as performing the assessments of new aviation safety products developed through NASA's Aviation Safety and Security Programme. For CFIT and LOC accidents, runway incursion, and engine failures, 20 specific BBN methods have been developed using case studies coupled with the expert knowledge. Causal factors have been identified from accident reports (Luxhoj and Coit, 2006). One of the first applications of the method in Europe concerned aircraft missed approach procedures. The BBN method is intended to capture the wide range of failures of aircraft systems both qualitatively and quantitatively, and thus provide objective and unambiguous information on the state of system safety for managerial decision-making (Roelen et al., 2003a, b). The sequences of individual events causing aircraft accidents are clustered into a number of scenarios initially modelled as trees with a logical and complete structure. Thus, the method contains technical and managerial components. In addition, it has been used as a decision-support tool to calculate the effects of specific changes in the aviation system on the overall risk, as well in supporting the development of proactive policies by providing insights into the effects of projected system changes on the risk.

Increasingly, causal methods have been used for gaining a better understanding of the effects of factors influencing the level of risk for evaluation of overall risk, risk communication and cost–benefit analysis of new technologies[2]; for the training of aviation staff and identification of system components that could be improved and for identifying "critical" causes of aircraft accident as well as measures for reducing risk. For example, when deciding the measures for risk reduction to be adopted, regulators and safety managers need an understanding of the causes of accidents and an ability to evaluate the benefits of various interventions (Spouge, 2004).

In terms of generalisations, the methods outlined, with the exception of CCA, are quantitative in orientations. Additionally, FTA, ETA and CCA are generally used to determine the statistical risk of occurrence of an accident or a failure of the system component, while Bow-Ties, TOPAZ and BBN are used for assessment of the predicted risk due to system changes such as the introduction of new technologies, procedures and operations. The causal methods are data driven and highly dependant in data quality, but also rely on expert judgements concerning the combinations of causal factors affecting air traffic accidents. In practice, quantification has often proved extremely difficult and time consuming mainly due to the complex combinations of causal factors involved.

In addition, calculation of probabilities and conditional probabilities in situations where dependencies between causal factors do not fully add are an additional complexity. The cumulative nature of these models is to make assessment of particular probabilities difficult due to the large number of causal factors and their combinations (Roelen et al., 2003a). Consequently, in some cases it has been rather difficult to express results from these models in a transparent and comprehensible way.

4. Collision risk models

One of the principal matters of concern in the daily operation of civil aviation is preventing conflicts between aircraft either while airborne or on the ground, which might escalate to collision. In addition, these include collision of aircraft with the terrain, which might happen after failure of the aircraft altitude indicator systems.

Although aircraft collisions have actually been very rare events contributing to a very small proportion of the total fatalities, they have always caused relatively strong impact mainly due to the relatively large number of fatalities per single event and complete destruction of the aircraft involved. In general, separating aircraft using space and time separation standards (minima) has prevented conflicts and collisions. However, due to reduction of this separation in order to increase airspace capacity and thus cope with growing air transport demand, assessment of the risk of conflicts and collisions under such conditions has been investigated using several important models:

- The Reich–Marks model was developed in the early 1960s by the UK's Royal Aircraft Establishment (Reich, 1966) and is based on the assumption that there are random deviations of aircraft positions and speeds from that expected. The model was developed to estimate the collision risk for flights over the North Atlantic and to specify appropriate separation rules for the flight trajectories (Shortle et al., 2004).[3] It computes

[2] Vismari and Camargo (2005) offer some specific discussion concerning new technologies.

[3] In 1964, the vertical and longitudinal separation standards in the North Atlantic airspace were 2000 feet and 20 min, respectively. The lateral separation between the tracks had been 120 nm. The International Air Transport Association (IATA) was aiming at reducing this lateral separation to 90 nm in order to increase the airspace capacity to handle current and prospective traffic growth.

the probability of aircraft proximity and the conditional probability of collision given that proximity.

Aircraft are represented as three-dimensional boxes, i.e., rectangular parallelepipeds of given length, width and height reflecting the ATC/ATM minimum separation rules. The collision might occur whenever any two boxes are intersected. As well, when one aircraft was represented as the dimensionless point, conflict occurred when the point entered the box. In such a context the collision risk with the vertical, lateral and longitudinal neighbour could be determined independently of each other bearing in mind that the position errors of boxes and points representing the aircraft along their tracks were random variables with zero mean and given standard deviations. Consequently, the prescribed lateral distance between aircraft could be specified with given probability of violation reflecting the acceptable collision risk (Federal Aviation Administration and European Organization for Safety of Air Navigation, 1998; Machol, 1995).

- The Machol–Reich model was developed after the International Civil Aviation Organisation (ICAO) had established the North Atlantic System Planning Group (NAT SPG) in 1966 aimed at developing the Reich–Marks model as a workable tool. Data on the lateral position errors for about 14000 flights over the North Atlantic indicating the lateral position errors of up to 120 nautical miles (nm) were collected (Machol, 1975, 1995). The modified model using actual data for the position error enabled prediction with moderate confidence regarding vertical, horizontal and longitudinal collision risks. The ICAO adopted the solution of including a fourth type of neighbour consisting of a “composite separation” in which additional aircraft were inserted with “diagonal–lateral separation” of 60 nm and vertical separation of 1000 ft. The solution nearly doubled the capacity of North Atlantic airspace.

  The expected number of lateral collision accidents while using 90 and 120 nm lateral separations was 0.6 per 10^7 flying hours and 0.1 per 10^7 flying hours. The absolute magnitudes were not acceptable, but the relative estimates were considered fairly accurate. Consequently, the NAT SPG, after considering accidents from all ICAO member states and using the existing accident rate, adopted a threshold for risk of collision of two aircraft due to the loss of planned separation to be within the range of 0.45–1.2 accidents per 10^7 flying hours.
- The intersection models belong to the simplest collision risk group. They are based on assumptions that aircraft follow predetermined crossing trajectories at constant speeds. The probability of a collision at the crossing point is computed using the intensities of traffic flows on each trajectory, aircraft speeds and the airplane geometry. An early example of this type of models was developed by Siddiqee (1973), followed later by Geisinger (1985) and Barnett (2000).
- The geometric conflict models are similar to intersection models. They were developed in the 1990s and take the speed of any two aircraft as constant, but their initial three-dimensional positions are random. Based on extrapolating their positions in time, it is possible to geometrically describe the set of initial locations that eventually lead to a conflict. This occurs when two aircraft are closer than the prescribed separation rules (say 5 nm). After integrating the probability density of the initial aircraft positions over the conflicting region, the conflict probability can be estimated (see Paielli and Erzberger, 1997, 1999; Irvine, 2002).
- The generalised Reich model aims at providing designers of advanced ATC/ATM components with safety feedback following redesign of a system or technology. The model is based on hybrid-state Markov processes developed for risk and safety assessment in industries such as nuclear power and for chemical plants. Such a generalised collision model was developed during the 1990s and has been used as a part of the TOPAZ methodology assessing safety by identifying hazards relevant to a given air traffic scenario and quantifying risk and safety by Monte Carlo simulations of the Petri Net models. Identifying critical hazards enables the creation of a simulation model related only to the airspace in which collisions are likely to occur. The generalised Reich model can be used to further improve the efficiency of simulations (Bakker and Blom, 1993, 2002; Bakker et al., 2000; Blom et al., 1998, 2003a; Shortle et al., 2004).

Mostly the FAA has applied various modifications of the Reich model. These include efforts to increase the number of tracks and reduce the lateral and vertical separation minima from 100 nm and 2000 ft to 50 nm and 1000 ft, in the airspace between California and Hawaii in 1973/74 and between Japan and Alaska in 1981; to examine the adequacy of ICAO recommended lateral separation minima between high-altitude parallel routes defined by ground-based navigational aids in US national airspace; to reduce the vertical separation minima above Flight Level 290 (29,000 ft); to reduce lateral separation minima between aircraft approaching closely spaced parallel runways; and to assess the wake vortex induced accident risks occurring for different aircraft categories in terms of weight approach and land on the single runway[4]; to assess the collision risk between the simultaneously missed approach aircraft independently of the decision height, air traffic controller instructions and the mode of runway use; and to understand the influence of ATC/ATM on collision risk, including reduction of the nominal separation between the opposite traffic streams (Blom et al., 1998, 2003b, 2005, 2006; Kos et al., 2000; Speijker et al., 2000a, b; Van Baren et al., 2002).

The main driving force for developing collision risk models during the 1960s was the need for increasing airspace capacity over the North Atlantic. The models were used to see if reduced separation and spacing between the flight tracks would be sufficiently safe. The models have gradually been developed by Marks, Reich and Machol to the latest versions used in the TOPAZ methodology. Their main purpose has always remained to support decision-making processes during system planning and development through evaluation of the risk and safety of proposed changes either in existing or in new systems.

Although collision risk models have been used for more than 40 years, they have their problems. They are complex, and there are often high costs involved in collecting the enormous amount of data on aircraft three-dimensional positions necessary to define the relevant statistical distributions (Machol, 1975; Stachtchenko, 1965). Additional time and expertise for calculation of the credible risk intervals are needed (Everdij et al., 2006). The complexity of the method also makes it difficult for the non-specialist to understand the implications of actions and thus makes full public debate of issues a problem (GAIN, 2003). These problems are not getting smaller. New versions of these models such as those used in TOPAZ are even more complex because they embrace more details when calculating risks, such as possible failure of some technical systems or flight crew awareness or fatigue. These details causing deviations of the aircraft from their planed positions during flights are incorporated into the models using stochastic differential equations. In addition, complex relationships between the elements of the system (flight crew, aircraft, ATC/ATM system, other aircraft, etc.) are modelled using Stochastically and Dynamically Coloured Petri Nets (SDCPN). To

[4] This has enabled reduction of the ICAO prescribed separation minima from 5 nm to 3 and 4 nm and has consequently increased airport runway capacity.

produce a risk value based on the generalised Reich model, a Monte Carlo simulation is performed (Rouvroye and van den Bliek, 2002).

Further, relying on expert judgement in cases where historical data are not available or when their collection is very expensive removes some of the objectivity from the analysis. There is always the problem of engaging credible experts, especially in cases involving new system concepts.

5. Human error models

"Human error" is one of the most frequent causes of aviation accidents (Boeing Commercial Airplanes, 2006). It is defined as an incorrect execution of a particular task, which then triggers a series of subsequent reactions in the execution of other tasks, resulting in a serious aircraft accident. Mitigation problem is usually through the monitoring and modelling of human errors in the aircraft and ATC/ATM systems aiming at discovering and preventing them. A number of approaches have been developed:

- The Hazard and Operability (HAZOP) method developed in the early 1970s aims at isolating potential hazards, operability problems, and possible deviations from the actual system intended operational conditions, including estimating the probability of escalation into a serious event. The method deals with human errors in complex technical systems such as chemical and nuclear plants having human operator in their control loop. Later, the UK National Air Traffic Service (NATS) applied the method to aspects of planning and assessing hazards in operation of the national ATC/ATM system, particularly identifying hazards due to human failures that could develop into a risk of accidents. HAZOP can provide input to FTA and ETA.
- Human Error Assessment and Reduction Techniques (HEART) were developed in 1985 for identifying and quantifying errors in an operator's task. They simultaneously consider ergonomic and other environmental factors that might compromise operators' performance. The impact of a particular factor on an operator's action while performing particular tasks is quantified and the probability of error in executing a task is estimated. The method consists of several components: classification of the generic task type; assignment of nominal probability of the operator's error; identification of conditions generating errors; determination of the assessed proportion of affect; calculation of the final probability of the operator's error; and considering the error reduction measures. The method has been applied by the UK NATS, in combination with other methods, for identification of potential human errors in two ATC/ATM en route sectors of the national airspace.
- The Technique for the Retrospective Analysis of Cognitive Errors (TRACER-Lite) was developed in 1999 by UK NATS, for predicting human errors and deriving error prevention measures in ATC/ATM. The method is retrospective and is used for classifying types of errors contributing to air traffic incidents that have happened. The method has a modular structure with three modules: the context; the error discovery; and the error recovery. They are represented as a series of colour-coded decision flow diagrams and associated tables. Hierarchical task analysis enabling identification of the "set of critical" tasks, critically influencing safety, usually classifies the human errors. The UK NATS has originally developed the method in order to improve understanding of ATC/ATM controllers' errors. The method has been applied for the analysis of errors causing AIRPROX incidents in UK national airspace during the period 1996–1999. Most recently, the method has been applied to EUROCONTROL projects—Time-Based Separation During Approach and Airborne Separation Assurance System (ASAS) concept.
- The Human Error in ATM (HERA) approach, developed at EUROCONTROL in the beginning of the 2000s, is a retrospective method providing insight into ATC/ATM controllers' cognitive processes while dealing with air traffic incidents. It consists of a retrospective element for the incident analysis, and a prospective part using the information collected on the assessment of probability of human error in cases of compromised safety. The method is aimed at gaining a better understanding of the constraints and conditions under which ATC/ATM controllers operate. This is important in understanding controllers' incompliance with existing procedures and skill-related errors. The method does not provide insight into the operators' errors at other levels of ATC/ATM such as maintenance, management and regulation. The method has been applied to ATC/ATM safety management as a part of the EUROCONTROL staff educational and training system.
- The Human Factor Analysis and Classification System (HFACS) is a method developed in the US in the early 2000s to categorise latent and immediate causal factors associated with aviation accidents. It is based on analysis aviation accident reports, and its main purpose is to provide a framework for accident investigations and to serve as a tool for accident trends assessment. HFACS considers four levels of failure: unsafe acts; preconditions for unsafe acts; unsafe supervision; and organisational or cultural influences. The method was applied by the FAA Civil Aerospace Medical Institute to air traffic operational error reports (GAIN, 2003), as well as in NASA's ASRM to facilitate consistency in the use of disparate causal factors (Luxhoj and Coit, 2006).

The models dealing with human errors focus on aircraft crew and ATC/ATM controllers. They also consider factors in the operational environment that can cause errors, as well as calculate the probability of individuals making errors in performing given activities. Consequently, it will be expected that they will be applied to both operational and design stages of developing aviation systems. Specific types of models have given insight into the cognitive processes of the ATC/ATM controllers operating in the incidental situations, analysed these situations, and calculated the probability of making errors. In addition, these models have possessed some ability for predicting errors and specifying the error reduction measures.

Human error models possess some shortcomings, which might compromise their more efficient and effective application to the ATC/ATM. Most activities in ATC/ATM and, in particular, factors influencing human operator performance and possible errors have usually been considered in isolation, i.e., independently of each other; in many cases the quantitative information has exclusively relied on expert judgement. In addition, use of these models effectively requires considerable training in psychology. These methods are also time consuming and almost impossible to be used in an operational environment without such specialists. The uses of the models are also limited, having been used exclusively on operational processes and activities in the ATC/ATM.

6. Third-party risk models

Third-party risk concerns risk to an individual on the ground of being killed or injured by crashing aircraft—a groundling accident or crash. Since most air accidents (about 70% according to Boeing Commercial Airplanes, 2006) happen around airports, the assessment of third-party risk has been mainly focused on this domain. Three cases of assessment of third-party risk are illustrated:

- The US generally assesses the risk of an individual when exposed to some distance from an airport during a given period of a year. Official statistics on fatalities from the US National Transportation Safety Board are collected and the number of potential ground fatalities estimated by multiplying the number of crashes around airports and the number of fatalities per crash. After expanding estimates to the entire US airspace and airport network, they have shown that the probability of being killed by crashing aircraft around an airport is 1.3×10^{-8}. The corresponding 70-year lifetime risk is equal to 9×10^{-7}. In addition, the model has shown that the probability of being killed by crashing aircraft has decreased more than proportionally with increasing distance from the airport and increased with increase in the volume of the airport traffic at distances up to about two miles. A limitation of the model is that it does not consider spatial variability of risk due to changing residential location patterns and aircraft flight paths around the airports (Rabouw et al., 2001). Fig. 2 shows findings for the top 100, 250 and 2250 US airports.
- The Netherlands has focused on the risk around Amsterdam Schiphol airport. In addition to continuous expansion of the airport closer to populated areas, and vice versa, the main impetus to more deeply consider the third-party risk was the crash of the El Al Boeing cargo aircraft in the Bijlmer district of Amsterdam in 1992 killing 39 residents and four-crew members (Hale, 2002). Consequently, three measures of third-party risk have been defined: the individual risk, the societal risk, and the risk of potential loss of life over the year (Ale, 2002). In addition, the method for calculating third-party risk around airports was developed by the NLR and contained the following elements (Ale et al., 2000): the accident probability model, which calculates the probability of an aircraft accident in the vicinity of an airport depending on the probability of an accident per aircraft movement (landing or take-off) and the volume of airport traffic (aircraft movements) carried out per year; the accident location probability model, which calculates the probability of a given location becoming an accident scene depending on its position relative to airport runways and the incoming and outgoing aircraft trajectories; and the accident effect model, which combines output from both previous models to calculate the probability of an accident at each location within the area surrounding a given airport.

  The model uses inputs such as the size and terrain characteristics of the affected area and lethality of the accident effects (for individuals on the ground) as dependant on the characteristics of the aircraft involved. Individual and societal risks have been the commonly used measures. The former has been defined as the probability that an individual residing at a particular location around an airport is killed during a year as a direct consequence of an aircraft accident. After calculating the individual risks for the entire area around a given airport, the risk contours can be plotted on the horizontal plane (Fig. 3). Societal risk, defined as the probability that a given number of people are killed as a direct consequence of a single aircraft accident, applies to the area around a given airport and exists only when people are present in the locale. Fig. 4 shows the basic idea. The risk of a single fatality rises, but at a decreasing rate, with the number of people living near an airport.
- The UK introduced public safety zones (PSZs) in 1958 that defined areas adjacent to the end of a runway where development of land is restricted if it would significantly increase the number of "residing, working or congregating people there". In the 1990s the method for third-party risk assessments around airports and the proposal of the appropriate risk assessment criteria was developed in *Third Party Risk near Airports and Public Safety Zone Policy*. The method was based on distinguishing aircraft by their manufacturer, country of origin, type (large, small, jets, turbo-props), and category

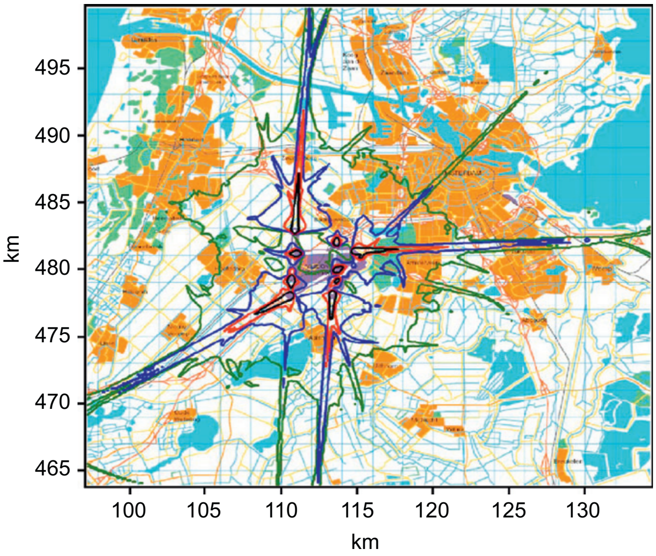

Fig. 3. Individual risk contours—Amsterdam Schiphol International Airport (for 2015). *Source*: Compiled from Ale et al. (2000).

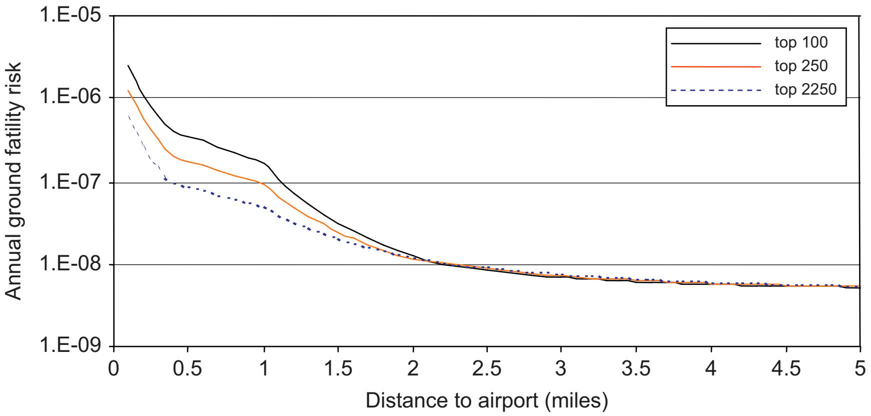

Fig. 2. Dependence of the risk of groundling fatalities around airports. *Source*: Rabouw et al. (2001).

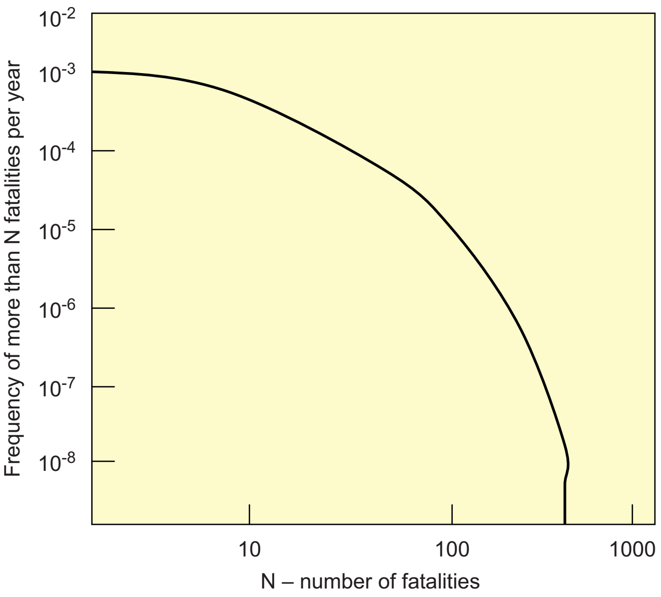

Fig. 4. Example of assessment of the societal risk at Amsterdam Schiphol International Airport. *Source*: Compiled from Pikaar et al. (2000).

(passenger, cargo), modelling of the aircraft crash location and the crash consequences based on a limited sample to draw risk contours. In addition, cost–benefit analysis was applied to establish criteria for acceptable risk levels. Consequently, this risk did not exceed one per 10^{-4} per year, which was in line with the tolerable risk at nuclear and chemical plants, and new buildings were not allowed within the 10^{-5} risk contours (Ale et al., 2000).

Third-party models have been mainly used for decision-making and policy purposes related to airport development and operations. They are used to forecast risks of an individual being killed by a crashing airplane in the vicinity of given airports; information that has been used for comparing risk around airports and that around chemical or nuclear plants. Zoning around airports based on individual risk contours and societal risk values, together with changes in these, is now undertaken in many countries. These models are not, however, without their problems (Hale, 2002). They lack generality and a specific model has to be developed for each airport. Proactive assessment of the risk cannot often be adequately carried out due to the risk control measures already in place. There is also a scarcity of official data on real accidents and risk exposure around the airports that adds to the difficulty of setting up threshold values for individual and societal risk; if these are too high it can compromise the airport's operations and development, but if too low can put individuals in unacceptable jeopardy.

The first problem has been addressed by making the models developed for particular airports more general (Amsterdam Schiphol in case of NLR) so that they can be applied to other airports with "similar" characteristics in terms of traffic volumes, aircraft fleet, and spatial layout, land-use and population density. The second problem has been impossible to address deeper. The third problem could not be addressed better simply because the accidents and the third-party fatalities around airports are rare events, thus preventing collection of the required amount of data. The last problem has been resolved by improving accuracy in setting up the thresholds for third-party risk around given airport.

7. Conclusions

Air transport policies have aimed at increasing system capacity on the one hand and reducing acceptable risk and safety thresholds on the other. This paper reviewed methods available for the assessment of risk and safety in civil aviation by dividing models along four lines; causal models for risk and safety assessment of the aircraft and ATC/ATM operations; collision risk models; human factor error models; and third-party risk models. It also highlights the uses and challenges posed in the use of such models. Their inherent complexity and lack of sufficient flexibility, inadequacy of available data for calibration and testing, and lack of sufficient predicting capabilities limit their effective application to the assessment of risk and safety of new technological, procedural and operational concepts. In many cases, the need for developing specialised or dedicated models for particular parts of the system has been found useful. In addition, the lack of suitable data has been overcome by including expert judgement despite awareness of the uncertainties and biases inherent in doing so.

There are clearly emerging challenges in applying the various procedures, and many are very issue or context specific in terms of their comparative advantage. The situation will become more complicated in the future, as Vismari, Camargo (2005) and others have highlighted in their works, because of the rapid developments that are taking place in technology as well as the continued expansion of the air transportation market and the greater influence of market forces within it. It seems inevitable that this will require new thinking on the best ways to assess risk and to develop appropriate strategies to handle it, as well as the need to refine the models that are already in place.

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