A causal model for the assessment of third party risk around airports

Feasibility of the development of a causal model for the assessment of third party risk around airports

Main Report

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Executive summary

Third party risk for airports covers risk to the population outside an airport area. In the Netherlands it is calculated with the use of a quantitative risk assessment (QRA) model that was developed by the Dutch National Aerospace Laboratory NLR. This model is based on historic accident data and is limited in its ability to assess the potential effects on third party risk of safety related measures. In this respect, it is not a tool for pro-active safety improvement. A causal model would better fulfil the need to predict quantitative effects of specific changes or measures to the level of risk.

This report focuses on the feasibility of the development of a causal model for the assessment of third party risk around airports. A causal model is a computational structure that formalises knowledge on cause-effect relations. Three basic types of causal models are considered in this respect:

1. Causal statistic - static;
2. Causal probabilistic - static;

The static causal statistic model is based on historical data and provides a good evolutionary basis for many types of causal models. Such a model can be developed from the causal analysis of accidents and incidents. The accidents are clustered into logical scenarios which are then modelled by means of fault trees and event trees. In a static causal probabilistic approach, expert judgement is used to fill gaps on available data in fault and event trees. Dynamics may be introduced to reflect that probabilities of occurrence of causal factors can change rapidly over time.

Beyond about 5 or 6 levels of a fault tree the events are influenced very strongly by influences of common mode factors, leading to a combinatorial explosion of the trees. The breaking down of the fault tree must stop at the level where common mode influences occur. The core of the model, which represents factors that directly influence safety, ends here. Factors that indirectly influence safety, such as management factors, should me modelled differently.

Modelling of management should be done by breaking down the quality of management into different common mode factors, where these factors can individually influence the probability of occurrence of the base events of the fault tree.

The aviation system can not be considered static for the purpose of risk assessment. The probability of some causal factors changes significantly over time. It are rapid changes over time, particularly where several factors vary together or where time dependencies are important, that will require dynamic modelling.

Criteria are presented for the assessment of the feasibility of a causal model. Three groups of feasibility criteria are analysed: Technical feasibility, relevancy for policy development and linkage with existing projects.
The results suggest that the most feasible approach for the development of a causal model is to divide it into phases. The start is the development of the core causal model, together with the identification of the functional elements which require more detailed modelling. Parallel to this phase, the possible structure of a management model can be explored. This parallel work provides a greater potential for the interfacing of the core and management models at a later date and also offers more insight than available from the core model alone. Following on from this, areas for dynamic modelling in both the technical system and the management systems can be identified which will offer greater potential for model improvement in terms of predictive accuracy and reduction of uncertainty. One of the greatest uncertainties of a causal model is in the adaptive behaviour of human and human-technical interactive systems. It is likely, however, that it is in these areas that the greatest payoffs will be achieved rather than in further detailed analysis of the easy to model and known factors.
### Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
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<tr>
<td>ATC</td>
<td>Air Traffic Control</td>
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<tr>
<td>ATIS</td>
<td>Automatic Terminal Information Service</td>
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<tr>
<td>CFIT</td>
<td>Controlled Flight Into Terrain</td>
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<tr>
<td>DUT</td>
<td>Delft University of Technology</td>
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<td>FAA</td>
<td>Federal Aviation Administration</td>
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<tr>
<td>FANOMOS</td>
<td>Flight Track and Aircraft Noise Monitoring System</td>
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<td>FSF</td>
<td>Flight Safety Foundation</td>
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<tr>
<td>GDR</td>
<td>Group Decision Room</td>
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<tr>
<td>GPWS</td>
<td>Ground Proximity Warning System</td>
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<tr>
<td>ICAO</td>
<td>International Civil Aviation Organization</td>
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<tr>
<td>IFR</td>
<td>Instrument Flight Rules</td>
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<tr>
<td>IVMS</td>
<td>Integraal Veiligheids Management Systeem (Integral Safety Management System, Schiphol)</td>
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<td>JAA</td>
<td>Joint Aviation Authorities</td>
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<td>JSAT</td>
<td>Joint Safety Analysis Team</td>
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<td>JSSI</td>
<td>JAA Safety Strategy Initiative</td>
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<td>MEL</td>
<td>Minimum Equipment List</td>
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<td>NLR</td>
<td>Nationaal Lucht- en Ruimtevaartlaboratorium (National Aerospace Laboratory, The Netherlands)</td>
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<tr>
<td>PRA</td>
<td>Probabilistic Risk Assessment</td>
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<td>PRIMA</td>
<td>Process Risk Management Audit</td>
</tr>
<tr>
<td>PSF</td>
<td>Performance Shaping Factor</td>
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<tr>
<td>QRA</td>
<td>Quantified Risk Assessment</td>
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<tr>
<td>RLD</td>
<td>Rijks Luchtvaartdienst (Directorate General of Civil Aviation, The Netherlands)</td>
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<tr>
<td>SID</td>
<td>Standard Instrument Departure</td>
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<tr>
<td>STAR</td>
<td>Standard Terminal Arrival Route</td>
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<tr>
<td>VOLMET</td>
<td>Meteorological information for aircraft in flight</td>
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1 Introduction

1.1 Background

Among the actors within the aviation industry, there is a need for a model that provides insight into the specific factors that determine the safety situation around large airports. In current risk assessment methods the factors that determine safety can not be analysed independently. As a matter of fact, a proper systematic identification of safety influencing factors and their interrelationships has never been conducted. This situation is unsatisfactory as it impedes the assessment of effects of safety improvement opportunities and consequently risk control. For this reason, the Dutch Directorate-General for Civil Aviation has initiated this study into the feasibility of the development of a causal model for the assessment of third party risk around airports.

1.2 Study approach

A consortium of 4 partners (NLR, SAVE, DUT and NEI) conducted the study, each of the partners bringing their own expertise.

The National Aerospace Laboratory NLR, with specialists in all fields of aerospace engineering (including aircraft operations, technical systems, airports, air traffic control and human performance) brings in operational expertise. In addition, NLR has relevant experience on the field of causal modelling for aviation safety, such as the Traffic Organisation and Perturbation Analyser (TOPAZ), which is used for ATM safety analyses. NLR is leading European projects (DESIRE for DG-XII, ASTER for DG-VII) on the development of aviation causal models for policy evaluation and it has started development of a causal model for the Aeronautical Inspection Directorate of RLD. NLR has developed a method for the assessment of third party that is currently being used to analyse the safety situation of airports in the Netherlands and abroad. Continuous efforts are aimed at further refining this model.

SAVE is an independent consulting bureau in the Netherlands. It comprises six professional advisors, supported by a small technical team. These advisors carry out projects for government organisations and companies. Projects have been primarily concerned with the safety of working with hazardous chemicals in fixed installations and in transportation and fire department services. Each of SAVE's professional advisors have more than 15 years experience in their field of work.

The knowledge and experience of SAVE is in the following specific areas:

- Risk analysis and safety studies
- Safety management
- Psychology and human factors engineering
- Design of municipal and regional fire department services
- Fire safety in companies
- System analysis

The Faculty of Technology, Policy and Management of Delft University of Technology is the only faculty in the Netherlands with a Safety Science Group. The Safety Science Group has participated in the development of risk models for external safety of chemical installations, for different aspects of transport by
A causal model for the assessment of third party risk around rail and for airports. The group is experienced in the systematic elicitation and validation of expert opinion in safety studies.

The Faculty of Aerospace Engineering of Delft University combines knowledge on all aspects of aviation technology. The section Control and Simulation is co-developer of an advanced flight simulator (SIMONA) which is being used in research on control systems and concepts (for instance tunnel in the sky).

NEI is an independent organisation for economic research and consultancy. NEI Transport, the largest division within NEI, covers all modalities of transportation including aviation. It is experienced in the use of modelling techniques, for instance to determine the reaction of airlines on increases in fuel price.

The planned project duration was 12 weeks from start to finish. This short time span precluded a full-scale investigation including extensive literature reviews and consultation of all sector parties. The study team decided to build the study around the experiences and expertise of the different consortium members. A steering committee was set up, with representatives of RIVM, Schiphol Airport, the Directorate General of Civil Aviation, the Ministry of Housing, Spatial Planning and the Environment, the Ministry of Interior and Kingdom Relations and the Transport Research Centre of the Ministry of Transport, Public Works and Water Management. During three project review meetings, the steering committee provided feedback to the study team.
2 Definition of third party risk

2.1 Introduction

The concept of third party risk or external risk was originally developed in the nuclear and chemical industry. In these industries, the risk of the release of (large) amounts of toxic or radioactive materials needs to be controlled. External in this case refers to everything outside the plant, whereas internal refers to everything inside the plant. For the chemical and nuclear industry the distinction between external and internal safety is relevant because there is a range of additional risk measures, such as secondary containment, which can prevent an internal loss of containment leading to external effects. Measures such as the construction of a concrete dome around a nuclear reactor have been developed to prevent such effects to the near populated area.

The concept of external safety can also be used for transport systems, including aviation, but there are some differences that are relevant. The most important is the fact that aviation systems are not static and hence risks are produced outside the airport perimeters. This leads to the fact that risk containment at the source is hardly possible.

2.2 Third party risk for airports

Third party risk covers risk to the population outside an airport area. It is defined as the yearly probability to die in the vicinity of an airport as a result of an aircraft accident.

For third party risk analysis two measures of risk are mainly used which are also common to other types of risk analyses: Individual Risk and Societal Risk.

Individual risk is defined as: The probability (per year) that a person permanently residing at a particular location in the area around the airport is killed as a direct consequence of an aircraft accident.

Societal risk is defined as: The probability (per year) that N or more people are killed on the ground as a direct consequence of a single aircraft accident.

Strictly these risk values are accident outcome frequencies but for small numbers the difference is not relevant.

Individual risk is in most cases presented as iso-risk contours on a topographical map of the study area, while societal risk is presented as so-called fN-diagrams, which plot the frequency of occurrence of an event against the number of fatalities. An example of individual risk contours around an airfield is given in Figure 1, while Figure 2 gives an example of an fN-diagram.

Individual risk is location specific, it is present regardless of whether or not someone is actually residing at that location. Societal risk applies to the entire area around the airport and hence is not location specific within that area. Societal risk only exists when people are actually present in the area around the airport. In an unpopulated area, individual risk levels may vary from location to location but societal risk is zero by definition.
It could be argued that the current way of representing risk should also be reconsidered, but this aspect is explicitly outside the scope of the feasibility study reported here.

Figure 1: Example of calculated individual risk contours around an airport

Figure 2: Example of a fN diagram expressing societal risk
2.3 Assumptions

The assumption taken in this study is that the assessment of third party risk will be based in the future on the same or similar indicators as those that are being used today: individual risk and societal risk. It is assumed that the calculation schemes for risk contours will not essentially change and thus will require quantified input data, such as the probability of an accident and various other quantified parameters. The final deliverable of the causal model under study will therefore be the quantified input parameters for the third party risk calculation scheme.
3 Current methodology for the calculation of third party risk

3.1 General description

Third party risk at large and regional airports in the Netherlands is calculated with the use of a risk assessment model that was developed by the Dutch National Aerospace Laboratory NLR (Piers et. al., 1993).

This third party risk model consists of three main elements: accident probability, accident location and accident consequences.

1. **Accident probability:** The probability of an aircraft accident in the vicinity of the airport depends on the probability of an accident per aircraft movement and the number of movements (landings and take-offs) carried out per year. The probability of an accident per movement, the accident rate, is determined from historical data on numbers of movements carried out at reference airports and the number of accidents which occurred during those movements.

2. **Accident location:** In reality, the local probability of an accident is not equal for all locations around the airport. The probability of an accident in the proximity of the runways is higher than at larger distances from the runway. Also, the local probability of an accident is dependent on the proximity of the routes followed by arriving and departing air traffic. The probability of an aircraft accident is higher in the proximity to a route and decreases with increasing distance from the route. This dependence is represented by the accident location model which is the second main element of the current methodology. The accident location model is based on historical data on accident locations. The distribution of accident locations relative to arrival and departure routes or relative to the runway is modelled through statistical functions. By combining the accident location model with the accident probability, the local probability of an accident can be calculated for each location in the area around an airport.

3. **Accident consequences:** A person residing in the vicinity of an airport is not only at risk when an aircraft accident occurs at this person’s exact location, but also when an accident occurs in this person’s close proximity. An accident may have lethal effects at a considerable distance from the central impact location. The dimensions of the actual area are a function of the aircraft- and impact parameters (such as aircraft size, quantity of on-board fuel, impact angle, etc.) and of the local type of terrain and obstacles. Consequently, the size of the accident area is not equal for every location around the airport. The influence of the aircraft- and impact parameters and the type of terrain on the size of the consequence area as well as the lethality of the consequences are defined in the consequence model, the third main element in the current methodology. The lethality is in this respect defined as the actual probability of being killed within the consequence area.
3.2 Refinement of the model

The current model for the calculation of third party risk at large airports was updated in 1999. This update makes the model more accurate resulting in a better representation of the specific situation at the Dutch national airport, Schiphol. More Schiphol specific (causal) factors are taken account of in selecting reference airports and in modelling accident probabilities.

The following selection criteria for airports are applied to calculate accident probabilities:

- Availability of Terminal Approach Radar at the airport;
- Availability of ATIS and VOLMET at the airport;
- No obstacles higher than 2000 ft within 6 NM and no obstacles higher than 6000 ft within 25 NM;
- Climatological and operational circumstances not significantly different from Schiphol;
- At least 90% of all traffic originates from JAA countries or North America;
- More than 70% of all approaches are precision approaches;
- Only airports with more than 150,000 movement per year.

Applying these criteria leads to a set of 40 reference airports from which data are used.

In addition to these criteria, as a first step towards the representation of different levels of safety within the mix of traffic at airports, different accident probabilities are now being used for different aircraft generations. Three aircraft generations are distinguished, based on general design characteristics and the year of introduction of the aircraft.

For each generation of aircraft, the accident probability numbers are classified into different accident types depending on whether the accident occurs during take-off or landing phase:

- Take-off
  - Veer-off
  - Overrun
  - Overshoot
- Landing
  - Undershoot
  - Veer-off
  - Overrun
This gives 6 types of accident per generation. Because it is considered that the accident probability of 2nd and 3rd generation aircraft is the same for take-off/veer-off and take-off/overrun type of accidents, a total of 16 accident probability classes are used.

Advances have also been made with respect to modelling the actual spread of routes flown by different aircraft. Data of actual routes (provided by the FANOMOS system) are being used in estimating the distribution around the nominal track.

The reference period for data selection is 1980-1997. The updated model is based on a total number of 75 accidents with 95 million corresponding movements.

For accident location and accident consequence some causal variables are incorporated in the models. Other causal factors are taken into account indirectly in the accident probability model through the selection of airports with comparable characteristics, the distinction between aircraft generations and types of accident.

Additional refinements of the model are under consideration.

### 3.3 Applicability of the current model

In addition to calculating the current third party risk around an airport, the model can also be used to predict the effects on risk of potential changes related to the model variables:

- Changes in arrival and departures routes and the (preferential) use of runways;
- Changes in the mix of traffic, based on the three aircraft generations;
- Changes in the mix of traffic based on aircraft weight;
- Increasing or decreasing numbers of movements;
- New or alternative developments in (the location of) built-up areas near the airport.

However, the present model, as based on historic accident data, cannot be used to assess the potential effects on third party risk many of many (safety-related) measures. This includes operational measures, such as reduced cross-wind limits for approach and landing, both for the airport and the airline, and policy or management related measures, such as the introduction of a Safety Management System. Because of these limitations, the current model is more a risk measuring tool than a tool for pro-active safety improvement.

Current aviation safety analysis methods are in general not pro-active. Most of these methods are centred around the analysis of causes of accidents, and subsequently elimination of root causes in order to prevent the occurrence of similar accidents in the future. This re-active approach has resulted in significant safety improvements throughout aviation history. However, over the last two decades the average world wide accident rate has more or less stabilised and does not seem to be decreasing, despite continuous efforts to further improve safety. In order to achieve a further reduction in accident probability, the industry is increasingly searching methods for pro-active safety analysis; methods that can be better predict quantitative effects of specific changes or measures to the level of risk (RLD 1996). It is assumed that a causal model would better fulfil this need.
The current model for third party risk analysis is based on historical data. The effects of many of the changes to the system are not visible until they appear in the historical data trends; there is no predictive tool for this. Furthermore the risk assessment is based on averaging the data over the 40 reference airports. Although these are broadly similar in terms of the selection criteria mentioned earlier, they can differ in other respects, such as layout, equipment, operations and management. The current model does not take account of these differences to give more airport-specific risk figures. This is an unsatisfactory situation if we believe that such factors make a difference to the risk.

We cannot know what the differences might be until a methodology is available for analysing third party risk which includes quantifiable causal relations between safety influencing factors and the third party risk.

Knowledge on cause-effect relations can be formalised in the structure of a causal model. A causal model consists of three types of components: variables, their relationships and their effects on the system. Before performing any causal analysis at least it must be decided which variables must be included and how these variables interact.

Three basic types of causal models are considered in this respect:
1. Causal statistical - static model of relations between variables;
2. Causal probabilistic - static model of relations between variables;
3. Causal probabilistic - dynamic model of relations between variables.

A characteristic of the causal statistical approach is that cause-effect relations are based on statistical associations found in historical data. For this reason such a model has limited use for predictions, particularly for types of accidents which have not happened yet (or were not registered).

Nonetheless, this approach is an essential basis for all of the subsequent types of model. All require a thorough modelling of causal factors and the causal relationships between them. Such models can only come from, and be validated by a retrospective analysis. The model must shown to have a good fit with reality. Therefore it is important to take a look at historical data so that priorities can be derived regarding those elements of a causal model that would require the most detailed development, and patterns of relationships can be established. One way of selecting data is to examine both high probability and high consequence events in detail. High consequence events should not be overlooked just because they are the rarest events.

The current model that is used for the calculation of third party risk can be regarded as a causal statistical model, where the prediction of effects is based on the evidence that such effects are statistically coupled to the occurrence of certain variables, whose occurrence in the modelled situation can be quantitatively specified. No causal explanation or understanding is required. The current and future updates to the model described in 2.2 will expand the ‘cause’-effect relations to some extent, but do not represent the factors and their relationships according to a logical causal analysis (such as the form of a logic tree, for example). In summary, it is only a way of assigning accidents to categories for calculating frequency rates and no causal relations between the
factors are made explicit. This means that risk can only potentially be modified by manipulating the associated factors (like numbers of movements).

Development of a more fundamental causal statistical model, which makes the causal relationships explicit, could be done through the development of a multidimensional accident analysis system which takes account of the different dimensions of cause. Also a causal representation of relationships is needed which shows a better understanding of the structure of the causal influences and which can ultimately be used to assess their quantitative effects on the risk based on a method such as fault- and/or event trees (see below). Such methods could include the following:

- A limited set of mutually independent top events, representing all the different possible accident scenarios.
- Causal trees containing at least hardware and human action failures with the possibility of analysing failures in terms of deeper underlying influences, including:
  - Management and organisational factors (training, procedures, information, communication, co-ordination, etc.)
  - Regulatory and market factors (policy, standards, certification, pricing, competition, etc.).

However, the development of such a model which needs statistical data on the relationships involved, will not be successful if there are a large number of cases for which data are not available. Such a problem increases in the dimension of the deeper underlying causes. In addition the complexity of the relationships become hard to manage if treated by such a decomposition technique.

Nevertheless, a limited causal statistical model could be the basis for the following two models, and could even be regarded as an evolutionary necessity. In this model and in subsequent models the depth to which the causal modelling goes is a matter of choice, bearing in mind the complexity problems, but must at least go far enough to improve the predictive power of the model in taking account of safety improving measures.

Turning now to the static causal probabilistic approach, this is aimed at the establishment of causal relations that can be quantified with probabilistic techniques and not solely historical data. In addition to historical data, expert judgement is normally used to fill the gaps in available data on the failure events in the trees and the influences of management and other factors on the probability of failures. A static causal probabilistic model can be used for predictions, but the possibility of divergence also exists. Part of a causal probabilistic approach is the establishment of potential accident scenarios which have not necessarily happened in the past but which could nonetheless occur. The causal trees developed for such a model can be refined to contain the potentially quantifiable and mutually independent base and initiating events. Models of this type are normally built from a combination of fault and event trees. Common mode factors (dependencies) linking different branches of the tree present particular difficulties (e.g. quality of maintenance, training, and other management factors). Causal trees do not represent underlying system functionality and do not capture adaptive mechanisms found in work systems and their management. Since the effect of feedback is to move towards a steady state, changes (like safety improvements) will cause the system to readapt over time, and results are difficult to predict.

One solution to these problems is to interface the causal tree model with another type of model, representing for example management processes which influence the various events in the trees. These influence models can range
from simple lists of performance shaping factors to more complex interactive models taking account of interrelationships between organisational and regulatory factors.

The dynamic causal probabilistic approach is characterised by additional use of simulation techniques, which allows a better representation of time related effects. This enables some common mode dependencies to be handled, in particular those factors which vary together as a function of the stage of the flight, etc. In addition disaster response could also be modelled dynamically as simulations. More difficult would be to run the influence model of management factors as a simulation to investigate how influences change over time because there are so little data available, and the modelling in this field is very state-of-the-art.

The main drawback of dynamic modelling is the considerable effort required implementing such a model. Dynamic techniques do not offer a short-term solution. Considerable long term effort is required also to collect relevant data at the deeper cause levels involving adaptive human systems.

To develop the types of models described above, different modelling techniques can be used. Which techniques will be selected depends on the specific requirements for the model and the characteristics of the system that is being modelled. An overview of modelling techniques is provided in Annex 2.

Causal modelling is not a one-off activity. A model will always have to be updated as information about new accidents or incidents comes in, or as new technology (aircraft, procedures, etc.) are introduced. This is an activity which must take place whatever type of model is chosen.
5 Developing a causal model

In the previous section it was suggested that a good evolutionary basis for many types of causal models is a static causal statistical model. Such a model can only come from a thorough causal analysis of accidents and incidents. This section will start with a discussion on the logic of this core causal model, followed by a discussion on the extent to which such a model should be expanded both in depth and breadth. The aspect of quantification will also be discussed.

5.1 Development of the logic

The core causal model can be developed from the causal analysis of accidents and incidents. The accidents are clustered into logical scenarios. These scenarios are then modelled by means of fault trees and event trees. Fault trees are used to model combinations of initiating events, component failures and human errors that can lead to an undesired top event. Event trees are used for modelling scenarios, taking the top event of the fault tree as a starting point. This is illustrated in Figure 4. Because of the basic shape of this figure, with a tree expanding to the left and to the right of the top event, such a model is often called a bow-tie.

![Figure 4: Bow-tie schematic](image)

An important issue in this respect is the choice of a set of top events, which should be mutually exclusive and complete. No matter whether the model developed is causal statistical, or causal probabilistic, static or dynamic, this stage is essential.

The fault tree, a logical breakdown of causes of the top event, is necessary in order to model the "causal period". The failure events that are deep in the fault tree (more to the left in Figure 4) are usually more distant in time from the top event. If the necessary and sufficient basis events are prevented from occurring, the top-event also will not occur. Since there are a number of pathways leading to the top event (scenarios), they all have to be considered. The response (or recovery) period is usually modelled as an event tree (sequence of events in response to the top event leading to different outcomes)
with dependent probabilities along the various branches, leading to outcomes of varying seriousness. Each box in the event tree can also have its own fault tree (detailed causal model). These are necessary if we wish to understand what factors must be managed to ensure that the probability is kept as low as possible of following the branch leading to the serious consequences and as high as possible of following the complete recovery branches.

The purpose of the model will influence the selection of the top events and the relative size of the event tree and fault tree. For example, if "death" is selected as the top event the recovery failure has to be modelled in the fault tree repeatedly every time it occurs in combination with another failure event, and all and only death scenarios have to be modelled. This is possible but not efficient. Hence a critical decision in modelling is the selection of the point at which the shift is made from fault tree to event tree in order to optimise the efficiency of the model.

The list of top events must be able to capture events that are possible but have not (knowingly) occurred. Criteria for choosing the point at which to shift from fault to event trees are
(a) that it is possible to define a small number of mutually exclusive events which cover all possibilities at that point,
(b) they should represent a clear transition from "normal control" to abnormal conditions,
(c) after that point the demand on a number of known designed barriers or recovery measures like trained responses can be modelled leading to different event pathways and different outcomes.

An example of a list of top-events meeting these criteria is as follows:
1. Loss of safe path (no control problems)
2. Loss of power
3. Loss of structural integrity
4. Loss of control.

Top event 1 leads typically to controlled flight into terrain or collision with other aircraft, usually with no attempt at recovery, 3 renders recovery impossible, whilst 2 and 4 may render recovery possible, leading to the possibility of more controlled selection of location of emergency landing.

The accident location and accident consequence are an elaboration on the event tree side of the bow-tie. The event tree could end with the crash of the aircraft, which means that disaster response actions are not modelled. However, a separate disaster response event tree could also be developed as a further extension to the right of figure 4, modelling whether the crash leads to death or not as a function of fire-fighting, rescue, treatment, etc.
Essentially, the bow-tie is a cross section of all possible events. This is illustrated in Figure 5.

![Figure 5: The bow-tie represents a cross section of all possible events](image)

One of the characteristics of a fault tree is that safety influencing factors that occur much before the occurrence of the top event (sometimes referred to as latent factors and often management/organisational in nature) are located deep in the tree structure. In practice, this means that in order to capture these factors in the fault tree, the tree must be expanded enormously. Beyond about 5 or 6 levels of a fault tree however the events are influenced very strongly by many to many influences of common mode factors such as competence, procedures, maintenance, etc. This leads to a combinatorial explosion of the trees. Computer power can also not solve this problem, since the assumption in fault tree logic is that branches are independent events (i.e. not linked by common cause). Currently there is no definitive solution for the handling of common modes in a fault tree. Hence the breaking down of the fault tree must stop at the level where common mode influences start. The elements at that level must be linked to the most important common modes through an interface to another sort of model, preferably one with feedback loops representing the adaptive nature of human systems mentioned earlier.

The core causal model described above can be further developed by expanding it both in depth and in width. To help to do this in a systematic way it would be useful to split the problem into several elements.
A possible way of doing this is presented in Figure 6.

- A first element (Flight) is the flight of an aircraft in all its stages (taxi, take-off, initial climb, climb to cruise, and the reverse for landing). Every critical deviation from the normal situation could be modelled under one of the four headings given above for the top events. This also allows modelling of the different risk profiles at different flight stages.
- A second element (Pre-flight) are the pre-flight characteristics of the aircraft and its crew, such as the technical state of the aircraft (design & maintenance), the aircraft type, the level of training of the flight crew, the standard operating procedures of the airline, etc.
- A third element (Flight support) is the aviation-related processes and influencing factors that exist outside the aircraft system itself during its flight. Air Traffic Control is the main component of this.
- A fourth element (External factors) represents non-aviation system related factors, but which impact directly on the primary flight process. This includes factors such as weather, terrain, birds, etc. These cannot be directly controlled, but can be influenced, or at least predicted and taken into account by the crew, ATC, or other system actors in planning their actions.

For each of the last three elements (pre-flight, flight support, external) the factors with direct effect on the flight and deviations in it can be analysed in further depth to reveal the underlying organisational factors, as discussed above.

For additional insight into the type factors that influence third party safety, and the relative importance of those factors, an expert meeting was held at the Group Decision Room of Delft University of Technology. The results of this meeting are presented in Annex 1.

5.2 System boundaries

The system boundaries determine the "breadth" of the model. System boundaries determine which elements of the processes that take place at and around airports should be incorporated in the flight model. This is illustrated with the help of Figure 7 which presents these processes.
Currently the crash events which occur in the dark shaded part of figure 7 (approach, landing, go-around, fly over, take off and departure) are included in the risk assessment, provided that the aircraft crashes outside the airport perimeter. A causal model of these events, to be complete, will also include many initiating and base events drawn from the light shaded part of the figure. The choice of such a system boundary for the point of occurrence of the crash event (or loss of control event) is, from the point of view of the flight process, hardly logical. It would make much more sense to the actors in the process to include also the taxiing step from the moment of crossing the blue line on the airside of the gate, and to include the crash events occurring in the other airside steps of the shaded part of figure 7, which result in a crash inside the airport perimeter. The initiating and base events in the unshaded part of the figure leading to these additional events will show a great overlap with those for the crash events currently considered by the external safety model. If this is done, the model for external safety and that for accidents within the airport on airside can be easily combined. A model representing functional systems is therefore preferred.

For example, a distinction is drawn between deaths of passengers and crew and those of third parties according to the definition of external safety. Much of the causal modelling of third party deaths will overlap with the factors relevant to passenger, crew and employee deaths. With the addition of a few extra causal branches in the trees the specific issues relating to these groups can be covered. These relate, among other aspects, to the design for crash survivability, accident scenarios during taxiing and the action of response teams in rescuing those inside the aircraft. For users of the model concerned with improving total flight safety these branches are vital. For calculations relating only to third party deaths they can be ignored. Inclusion of all these aspects in one causal model ensures that external safety and other aspects of system safety are related to each other. This may well influence the acceptability of the model.
5.3 Depth of the model

The basic model (the bow-tie) can subsequently be expanded in "depth". Three aspects are important here:

- Modelling of management (indirect adaptive factors)
- Required level of detail
- Dynamics.

5.3.1 Management factors

Underlying all technical and human failures there are always management systems which were (or should have been) designed to prevent them but which failed to do so. An important question is whether, and if so how, these underlying management systems should be explicitly represented in the causal model. The expert meeting described in Annex 1 indicates that many of the factors that influence third party risk are 'indirect' factors, typically these are management and organisational factors.

The simplest way to incorporate management is by multiplying the probability of occurrence of the top event of the fault tree by a factor which expresses the quality of management. This is a reasonable approach when 'management' has a single common mode effect, whose management quality and its effects can be assessed and which is fairly stable over time. The aviation system, however, is very different to this. It has up to a hundred independent organisations managing the different causal factors and events in the tree. A co-ordinating management system in the shape of the integrated safety management system for Schiphol (IVMS) is only a recent development and can not (yet) be said to represent or guarantee a uniform and stable management quality. A more sophisticated (and for the aviation system a more appropriate) approach breaks down the quality of management into different common mode factors, where these factors can individually influence the probability of occurrence of the base events of the fault tree. This method provides much more insight, but of course requires much more effort to develop.

The question of how to make the link between the technical model (bow-tie) and the management model is a key question.

If the only objective is quantification of risks (which it is not, because a primary objective here is pro-active safety assessment), it is only needed to link other models to the technical model (fault and event trees) where the use of a generic average probability or frequency for a given factor or base event is suspect. The generic or average value may be unsatisfactory because there is a lot of variation around it, depending on issues such as how the related function is carried out and by whom, or it may be considered that it may change in the future with changing procedures or technology. Otherwise, the rule is to keep the tree as simple as possible. Apart from this, the main driver to proliferate the tree and the models attached to it should be to gain more insight into what is driving the risk.

A management model is essential if one of the objectives of the modelling is to be able to see how changes in the way operational and management functions are carried out will influence the probabilities of errors and failures and of initiating events. There are many ways of carrying out those functions, and the causal model must provide a tool that can help to choose between different options. The causal model must also show how much effect on risk there will be if the functions are carried out well or badly (by good or bad companies and operators) and whether there will be more risk taking behaviour with apparently safer systems.
Methodologies for modelling management aspects, in increasing level of sophistication, are the following:

- Performance shaping factors;
- PRIMA approach;
- I-Risk approach (stable state feedback loops);
- I-Risk dynamic approach (time related change).

These are described briefly in Annex 2 of this report.

The PRIMA modelling approach provides insight into the management factors influencing the accident risk, but does not permit this insight to be translated into a detailed quantitative influence. Both the PSF and I-Risk approach attempt to make detailed quantitative modifications at the level of base and initiating events, and are considered as alternatives for more advanced management modelling. The dynamic I-Risk approach is still in an early development stage and will need more fundamental research before it can be applied. It is not considered further as an option in this report, but we suggest that the actors in the aviation process should give support to this fundamental development for the longer term.

5.3.2 Level of detail

A limit must be set on the size of the tree and the depth of causes in the tree and the attachment of common mode influences and adaptive mechanisms. The degree of detail and sophistication of any given part of the model should be decided upon based on some sort of sensitivity analysis of how much that aspect could contribute to the overall risk figure. Only for major influences is further detailed modelling worthwhile.

The required level of detail also depends on the purpose of the model, ranging from global risk assessment to detailed risk management. A practical solution is to model first at a more aggregate level and with further detail in a next step, taking account of those elements to which the model appears to be sensitive or areas of specific interest (e.g. because one wants to analyse the effect of certain proposed safety measures or other measures which might compromise safety).

The more detail in the technical model (the bow-tie), the more insight is provided into failure mechanisms, but also the more demands are made on the time for, and the accuracy of the modelling. It is very easy to leave out complete branches in a fault tree, because the accident has not happened that way yet; because the logical reasoning is not good and exhaustive, etc.

On the other hand, statistical analysis also suffers from this problem, because an accident that has not occurred (yet) will not be included in the statistics. In this sense the completeness of a structured causal model that is based on accident data is no better than the statistical causal analysis alone. However, if incident data and systems analyses are used together, and this is done in a way which represents the functional aspects of the system, the completeness and usefulness of the model will improve.

Neither accident-based causal models nor those based on logical modelling can be guaranteed to be complete, but the gaps will probably be different, so that a combination of both approaches will leave less out.

Another limit on the level of detail is the level at which data about failure probability or event frequency are available. That level will depend on the available databases and on the potential level of detail that can be reached with
improved analysis of the existing accident and incident data or by improved
data collection for other factors. Where such data are not available, expert
judgement is the only feasible source of quantification pending long term data
collection. While certainly better than nothing, it has a number of drawbacks.
Among others there is a tendency to overestimate the effects of actions and
underestimate the resistance of an existing system against change. The
advantage is that it tends to make the key issues explicit. If systematically
elicted from experts who are both knowledgeable and well-calibrated for the
relevant area of expertise, it can offer quite acceptable accuracy of
quantification. In particular it is good at indicating the relative importance of
causal factors and at revealing areas of disagreement about control measures
which require additional research.

5.3.3 Dynamics
A system can be termed static with respect to risk when the behaviour of the
system does not change rapidly with time. The aviation system, and in
particular an aircraft in flight, cannot be considered static for the purpose of risk
analysis. The probability of some root events changes over time. For example
engine failure is more probable when high engine power is selected (such as
during take-off), and a critical underspeed (stall) is more likely during approach
than during cruise flight. In addition the available time for recovery, and
thereby the event tree for recovery, depends strongly on the flight phase.

Slow changes over time, such as influences from management, maintenance
and regulation do not need such dynamic modelling. It is only rapid changes
over time, particularly where several factors vary together (common mode), or
where time dependencies are important, that need dynamic modelling to arrive
at estimates for current risk levels. However, dynamic modelling, or at least
repeated runs of a static model with successive modification of the parameters,
may be relevant at another level to generate insights into future trends, as new
technology is introduced, or management quality varies under different
pressures. The dynamic management model mentioned in the previous section
and discussed in Annex 2 of this report is an example of this approach.

There are two possible approaches in a risk analysis for a system whose
behaviour can change rapidly with time. The first is a discretisation of the
dynamic character of the system, for example by considering short sections of
an aircraft’s flight. Fault tree probabilities, and the time available for the
recovery may differ for each section. In this manner the risk analysis is repeated
for each section of the flight.

A second approach is the application of dynamic techniques. Here the risk
model is combined with a dynamic simulation of the system, in this case the
aircraft. Effects of root events on the system are modelled, as well as the effect
of system state on the probability of root events.

An important characteristic of the division presented in Figure 5 is that it allows
a (crude) separation of dynamic and non-dynamic factors. Dynamic factors are
those factors in which the element of time plays an important role. Those
factors that are part of the “Flight” box are dynamic (especially in the take-off
/climb and approach / landing phase of the flight) The factors of the “Flight
support” and “External ” box can also be regarded as dynamic in this sense of
varying with the minute. The “Pre-flight” box is static compared to the other
boxes; it varies only over periods of days to years as do the underlying
management factors feeding the different boxes. For those aspects static
modelling is appropriate, or at most trend analysis as described above.
The critical period to make a significant difference to survival of a major accident is the first couple of hours. After that the differences are fairly small, assuming, as at Schiphol, a locally available well-equipped trauma hospital. This would mean that a disaster response tree would also have a dynamic section, followed by a static section.

5.4 Summary of choices

As described in the previous sections, the words "causal model" can be used to describe anything ranging from a simple cause-effect relation established by statistics to a detailed dynamic probabilistic tool enhanced with management modelling. The decision of where in this spectrum the development of the model should be aimed at depends on the objectives of the user and the resources that are available. In general, choices are needed on the following items:

- Level of detail of the bow-tie
- System boundaries
- The inclusion of management factors
- Which part of the model should be dynamic.

The first two bullets relate to the breadth and depth of the core causal model. A limited option would go no further than the current model, as recently updated, in the number of types of initiating or base event incorporated and would not include any of the additional airside events resulting in a crash within the airport perimeter. An advanced option would take the whole airside process as its system boundary for the place where the accident (or deviation) occurred, and would develop a fault and event tree model going into as much detail as feasible on the direct technical and operational events related to these crashes. It would not include the management (or other indirect) factors, but would extend the core model to cover the rescue process. In relation to the treatment of management factors, we recognise two options:

- a simple modelling using the PRIMA approach to gain insight into the relevant management factors, but incorporating them quantitatively only at a very generic level in the fault and event trees, and
- an advanced modelling using I-Risk or PSFs at a detailed base and initiating event level in the causal trees.

The final option is whether to model at least some of the highly dynamic parts of the flight process using the dynamic modelling techniques described. This will be rated as one option, though there are a number of sub-options relating to how many parts of the flight process are modelled in such a way. Choices at the sub-option level could be made based on the sensitivity of that part of the causal tree to time-varying events. Given the relative novelty of this sort of modelling, each part modelled would add considerably to the time and investment required. As with the dynamic management modelling, additional fundamental research for this part of the research would be strongly advisable.

These choices have to be based on criteria that are described in the next section.
6 Criteria

6.1 Introduction

The assessment of the feasibility of a causal model must be based on clearly defined criteria. For the purpose of this study, the selection criteria can be split into three different main groups:

1. Technical feasibility
   • Verification
   • Validation
   • Complexity
   • Availability of data
   • Development time
   • Knowledge intensity
   • Development cost
   • Degree of quantification of the end result

2. Relevancy for policy development
   • Prediction capabilities
   • Degree of understanding provided by the model
   • Transparency
   • Optimisation
   • Acceptance
     • Government
     • Residents
     • Airport authorities
     • Air traffic control organisations
     • Airlines
   • Purpose of the user
     • Enforcement
       • Airport capacity problems
       • Spatial planning
     • Improvement
       • Scenario’s
       • Cost/benefit analysis

3. Linkage with existing projects
   • Accident analysis
   • Development of causal model for internal safety
   • Development of safety performance indicators
   • Qualitative safety research for Schiphol Airport
   • Current methodology for third party risk analyses (including expected improvements of the methodology)
   • International studies

The following sections describe what are the most important issues linking the criteria to the types of models and the types of use the model is put to.
6.2 Technical feasibility

Verification and validation
The problems of verification and validation of the causal model will be the same as those faced by the current model for the calculation of third party risk. A causal model offers slightly more opportunities for verification and validation, because it can be used to predict the occurrence of incidents of a certain severity. This means that incident data can be used in addition to accident data for validation purposes.

Availability of data
The core of the model, (the bow-tie) needs to be built on detailed and structured analysis of aircraft accidents, requiring high quality data which in general can only be found in official accident reports. The difficulty of obtaining high quality information about accidents is a continuing problem faced by safety analysts. The Final Accident Report is without doubt the single most complete source of information regarding an accident. However these reports are not necessarily publicly available, and in many cases will require translation before they can be properly interpreted. In practice, accident reports of all accidents that have occurred in the US or some parts of Europe are publicly available. For other parts of Europe accident reports for some accidents are available, while reports of accidents that have occurred elsewhere are not available, except for some rare cases. In a recent extensive effort carried out for a European funded research project (Hayes et al, 1999), the (international) study team could only obtain 109 accident reports out of a total sample of 1066 fatal accidents and hull losses of Westerm built jets from 1970 onwards. Where data are not available, expert judgement must be used.

For a statistical model, the sample data are restricted to the accidents that have occurred in the vicinity of airports that have the same characteristics as the airport of interest. For a causal model, as the causal tree is split into smaller elements, it is possible to recognise comparable aspects in a much greater range of accidents which have occurred, and which can therefore be used to swell the database. The data sample does not need to be restricted to accident data. Incident data can be included because the cause-effect relations that lead to an accident are not different from those that lead to an incident.

In addition to accident and incident data, data on normal operations are required to determine the relative importance of factors that contribute on accidents. Under a contract awarded by RLD, NLR has been developing a database for this purpose. This Denominator database contains world-wide scheduled flight information from 1976 onwards, and information on all IFR flights within the Eurocontrol region from 1987 onwards. These data are linked to an aircraft database (containing technical and utilisation information on individual aircraft), an airline database (containing fleet and financial information), an airport database (containing information of 4000 airfields) and a world-wide weather database.

This database alone will not be sufficient however. Day-to-day operational data must be provided by those parties that generate the data, i.e. airlines and airport authorities. This means that co-operation of the sector is an essential requirement. It is recognised that this information can be very sensitive, and good agreements on confidentiality are needed between parties involved.

Assessing the quality of management (needed in a management model) requires the use of auditing techniques attached to a management model. As explained in section 4.3.1, an approach that is appropriate for the aviation
A causal model for the assessment of third party risk around a system breaks down the quality of management into different factors. Management of the different processes at an airport is not performed by a single actor. At least the most important management system functions should be identified and modelled before a full management model can be built.

Data is needed which shows the relative influence of different management factors on the various base and initiating events. This can be obtained to an extent from a deep analysis of available accident reports, but will certainly require to be supplemented by expert opinion. Another necessary step for the advanced management modelling is to calibrate the model, i.e. to compare the different quality of management of the various parts of the safety management system as carried out by different actors (e.g. airlines, maintenance contractors or ATC) and relate that quality to the range of failure/error probabilities or frequencies in the core model.

**Development time and cost**

Development time and cost will increase with increased "depth" of the model and the extent to which adaptive human systems are included. Development of the core causal model (bow-tie) could require an effort of approximately 2 man-years. Adding a rudimentary management model to the core model (using Performance Shaping Factors) would require an additional effort of 1 man-year. A more sophisticated approach, such as was used in the PRIMA study, could require 2 man-years instead of 1, while an advanced model (the I-Risk approach) would probably require 4 man-years instead of 1 to develop. The most complex management model (I-Risk dynamic) would require fundamental research first.

Enhancement of the model by the introduction of dynamics would require an additional effort of at least 4 man-years for a single class of aircraft (like 3rd generation Airbus). The additional effort that is required to model other classes of aircraft will depend upon the nature of the differences in the operation of the aircraft with respect to the class that has already been modelled, and is difficult to predict here.

The selection of the system boundaries has some influence on the development effort that would be required. Expanding the model with elements such as taxiing accidents, crash survivability and disaster response would require an additional effort of approximately 6 to 8 man-months. The total effort involved in the development of a causal model with proper modelling of management aspect would therefore require a total effort of approximately 6-8 man-years. Addition of dynamic modelling would add anything between 4 and 12 man-years, depending on how many aspects were to be modelled this way.

Increased sophistication of the model will provide the user more insight into the factors that influence safety. In this respect it is important to note that even simple management models such as the use of performance shaping factors or the PRIMA approach do provide insight into the management factors that influence safety, but insight into the adaptive mechanisms of human system performance can only be achieved by advanced (I-Risk type) management models.
Table 1: Development time estimates

<table>
<thead>
<tr>
<th>Element</th>
<th>Development time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core causal model</td>
<td>2-2½ man-years</td>
</tr>
<tr>
<td>Expansion</td>
<td>0.5 - 0.7 man-years</td>
</tr>
<tr>
<td>Management model</td>
<td></td>
</tr>
<tr>
<td>PRIMA approach</td>
<td>2-3 man-years</td>
</tr>
<tr>
<td>I-Risk approach</td>
<td>4-5½ man-years</td>
</tr>
<tr>
<td>Introduction of dynamics</td>
<td>4-12 man-years</td>
</tr>
</tbody>
</table>

The core causal model and the management model can largely be developed in parallel, the calendar time for development of the core model and management model is estimated to be approximately 3 years. Assigning more manpower will probably not decrease the calendar time, because of the time needed to gather the data. True dynamic modelling can only start after the core causal model has been developed, although fundamental research into this aspect can start as early as the start of the development of the core.

**Knowledge intensity**

Development of the core model requires the combination of thorough knowledge of the aviation system, both technical and operational and a sound mathematical background. An important aspect of developing the management model will be the choice of the modelling and audit teams that will identify and assess the quality of the important management functions. The modelling and audit team should combine knowledge of management system modelling with experience with auditing, technical knowledge of the aviation system, and skills in interviewing and interpreting information from those interviews. The introduction of dynamics requires technical and operational knowledge of the aircraft, knowledge on performing and interpreting task analysis, and knowledge of and experience in the mathematics behind dynamic modelling.
### 6.3 Relevancy for policy development

**Prediction capabilities**
The prediction capabilities of the model, or the capabilities of the model as a tool for safety improvement rather than safety assessment, will increase if the number of input parameters is increased. Increasing the detail of the core model and adding a management tool will increase this capability as will adding dynamics for the safety-critical phases of flight.

**Degree of understanding provided by the model**
The degree of understanding provided by the model increases with increased detail of the core model, and will increase if a management model is added to the core, particularly if an advanced (adaptive) management model is developed. Dynamic modelling will also increase the understanding of the core aspects of the risk of the flight process, in particular the take-off and landing, which may make significant changes in particular to the crash location modelling.

**Acceptance**
Acceptance of the model will be influenced by the way in which the model allows the representation of safety enhancing measures that have been taken by the various actors in the system. This is one of the points of criticism against

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1 This assessment is the opinion of the researchers and is not based on discussion with the actors directly.
the current method for the calculation of third party risk. The current model is based on statistical data, and although the data was collected for Schiphol-like airports only, the specific measures that have been taken at Schiphol to further increase safety and Schiphol specific factors that could decrease safety are not represented.

Acceptance by the airport authorities will increase if the model includes an advanced management model. A management model is necessary to show the effect on the risk of the implemented Safety Management System at Schiphol airport. Potentially, the model could then be used by the airport authorities to support decisions with choices that have to be made between different options. Acceptance by the airlines will increase if the causal model allows true dynamic modelling of the flight phase. This is necessary to show the effects of typical airline-controlled parameters such as crew training, Standard Operating Procedures, etc. These parameters are expected to influence the dynamic behaviour of the flight crew, specifically in the take-off, approach and landing and in emergency situations.

**Purpose**

If the results of the model are to be used as a tool for enforcement, the requirements for the quantification of the end-result are much more stringent than the requirements for a model that has the purpose to gain insight into those factors that influence safety, and the relative influence of each of those factors. The results of an enforcement tool should preferably change little with ongoing development of the model, as this would undermine its use. For a tool that is intended to gain insight, it can be allowable that the quantified results of the model are different in subsequent development stages of the model, as long as the changes are relatively small.

A proper dynamic model will better describe reality and potentially enables better modelling of the accident location and accident consequence, including disaster response.

Use of expert judgement must be carefully thought through if the purpose of the model is enforcement. Expert judgement can be expected to become a subject of discussion, which would again undermine the acceptance of the model as a tool for enforcement.

Experience with the current model for the calculation of external risk around airports has shown that sector parties would like to be involved during the development process rather than being confronted with a "black box model". While participation of sector parties is strongly encouraged, experience has also shown that this could result in much political debate on policy decisions rather than technical decisions. Discussion on policy decisions should be separated from the technical discussion as much as possible. Interference between the two can easily lead to a slowdown if not stand still of the technical model development.

### 6.4 Linkage with existing projects

The detailed analysis of aircraft accidents by accident investigation teams with the objective to identify root causes that can subsequently be eliminated is an approach that has been used from the early days of aviation. The industry, realising that a broader approach is necessary to further increase safety, has now started a number of new initiatives that focus on a systematic analysis of groups of accidents with similar characteristics. Examples are the Flight Safety Foundation (FSF) / ICAO CFIT Task Force, the FSF Approach and Landing task
A causal model for the assessment of third party risk around Force, the US Joint Safety Analysis Teams (JSAT) and European JAA Safety Strategy Initiative (JSSI). JSAT subjects have been:

- Controlled Flight Into Terrain (CFIT),
- Approach and Landing,
- Loss of Control.

JSAT and JSSI groups have in common that they include representatives from all parts of the industry.

The results of the analyses by these teams can be used directly for building the causal tree structure. Linkage and co-operation with JSSI and JSAT initiatives is further advised because participants are valuable and in most cases willing points of contacts in the ever-lasting search for data.

The Flight Safety Foundation (FSF) in the US has initiated an effort in modelling risk with the Flight Operations Risk Assessment SYSTEM (FORAS). The FORAS system is intended to be a measurement system that can determine the relative risk of an accident or incident for each particular flight (Hadjimichael, 1999). The risk assessment value is presented as a number between zero and one. This is a relative value and therefore only meaningful when compared to a baseline or previous value. A weighed combination of safety influencing factors is used to produce a single relative risk assessment value.

Preliminary model development, based on work of FSF’s CFIT task force, yielded CFIT risk categories and weightings. As examples, figure 8 presents the approach/departure division, and figure 9 a day/night division. The factors and associated weightings are purely based on the expertise of aviation experts.

![Diagram of FORAS top level hierarchy for CFIT risk](image)
Figure 9: FORAS day/night branch of CFIT risk hierarchy

The resemblance between figures 8/9 and the left hand side if figure 4 may be noticed. Elements of the FORAS system could well be used during the development of the core model. Alternatively, the FORAS team would benefit from the development of a causal model as this could take the system a step beyond mere expert judgement. Linkage and co-operation with the FORAS project is strongly advised.

The projects related to the development of a causal model for "internal" safety and Safety Performance Indicators (Roelen 1999 I & II) provide a convenient starting point for the development of a management model. These projects have established a proper list of management related factors that influence safety, and a first indication of the degree of influence of those factors on other safety influencing factors. The I-Risk results can be used both for building the structure of the management model and for setting up audits that are needed to subsequently acquire data.

Various qualitative and quantitative safety research studies have been conducted for Schiphol airport or airports in general (Vandel 1995, Kruijsen 1999, van Es 1999 I and II). The results of these studies can be used in the development of the core causal model.
The current methodology for third party risk analyses, with the expected improvements provides a convenient starting point for the development of the core causal model. The current model is already showing some rudimentary cause-effect relations, and these will be extended with the ongoing development of this method.

The Integrated Safety Management System (IVMS) at Schiphol provides both a potential user of the model and a source of data for both the core causal model and the management model, especially from the recent Dupont qualitative safety study of the management systems and IVMS at Schiphol.

FAA has launched the Aviation Safety Risk Analysis Program (ASRAP) to develop analytical and decision support tools for aviation safety inspectors. It draws heavily on the Safety Performance Analysis System (SPAS). The FAA began developing SPAS in 1991, and it is intended to analyse data from up to 25 existing databases that contain such information as the results of previous airline inspections and the number and nature of aircraft accidents.

SPAS program officials have acknowledged that the quality of the information in the databases that are linked to SPAS poses a major risk to the system. Continuing problems with the quality of the data entered in the various source databases for SPAS have been reported.

Although SPAS is primarily a tool intended for FAA inspectors, the system could potentially be used as a valuable source of data. In addition, the current users of the SPAS system will be able to provide valuable feedback on both causal relations as well as the use and integration of large datasets. Further exchange of information and possibly co-operation with the SPAS team should be encouraged.

The dynamic modelling is the approach which requires the most fundamental new research, which can draw only in a limited way on previous work.

6.5 Comparing modelling options with criteria

Table 2 summarises the comparison of the different modelling options with the criteria. The table lists two options for both the core model and the management model: simple and advanced. In reality, there will not be a clear-cut distinction between a simple and an advanced model. There will rather be a continuum in opportunities ranging from simple to advanced. The table should be interpreted accordingly.
### Table 2: Comparison of modelling options with criteria.

<table>
<thead>
<tr>
<th></th>
<th>Core model</th>
<th>Dynamics</th>
<th>Management model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simple</td>
<td>Advanced</td>
<td>Simple</td>
</tr>
<tr>
<td>Verification and validation</td>
<td>😊😊</td>
<td>😊</td>
<td>😊😊</td>
</tr>
<tr>
<td>Complexity</td>
<td>😊😊</td>
<td>😊</td>
<td>😊😊</td>
</tr>
<tr>
<td>Availability of data</td>
<td>😊😊</td>
<td>😊</td>
<td>😊😊</td>
</tr>
<tr>
<td>Development time</td>
<td>😊😊</td>
<td>😊</td>
<td>😊زا</td>
</tr>
<tr>
<td>Knowledge intensity</td>
<td>😊😊</td>
<td>😊</td>
<td>😊زا</td>
</tr>
<tr>
<td>Development cost</td>
<td>😊😊</td>
<td>😊</td>
<td>😊زا</td>
</tr>
<tr>
<td>Degree of quantification of the end result</td>
<td>😊</td>
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<td>😊زا</td>
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<tr>
<td>Prediction capabilities</td>
<td>😊</td>
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<tr>
<td>Degree of understanding provided</td>
<td>😊</td>
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<tr>
<td>Transparency</td>
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<tr>
<td>Optimisation</td>
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<tr>
<td>Acceptance[2]</td>
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<tr>
<td>Government</td>
<td>😊</td>
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<tr>
<td>Residents</td>
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<tr>
<td>Airport authorities</td>
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<td>ATC</td>
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<tr>
<td>Purpose of the user</td>
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<td>Airport capacity problems</td>
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<tr>
<td>Spatial planning</td>
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<td>Scenario’s</td>
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<tr>
<td>Cost/benefit analysis</td>
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<tr>
<td>Linkage with existing projects</td>
<td>😊</td>
<td>😊</td>
<td>😊</td>
</tr>
</tbody>
</table>

😊 = Not difficult, many possibilities, not much effort required.
😊😊 = Neutral.
😊😊😊 = Difficult, limited possibilities, requires much effort.

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2 This assessment is the opinion of the researchers and is not based on direct discussion with the actors.
A causal model for (third) party aviation risk should consist of a tree-like core causal model, which can be expanded in both breadth (system boundary) and depth (management, level of detail, dynamics). The development of the core model is without question feasible. Whether the subsequent expansion in breadth and depth is feasible depends on the importance that is assigned to the specific characteristics of these elements.

The tree-like core is a static statistical causal model. Fault trees and event trees are used to model accident scenarios. The current methodology for third party risk analyses provides a convenient starting point for the development of the core causal model. Existing accident analysis projects (such as JSAT and JSSI) and qualitative research studies provide direct input for the development of a core model.

The breadth of the model is determined by the selection of the system boundaries. It is strongly suggested not to base the selection of the system boundaries on the difference between external and internal safety as defined by the airport perimeter. It is much more appropriate to use the functional boundary of the airside processes at the airport as the system boundary and to model the functional systems.

The depth of the model can be increased by:
- Modelling of management
- Increasing the level of detail of the core model
- Introduction of dynamics in (parts of) the model.

Management modelling offers clear additional benefits, which are desired by the sector parties. An important question is to what extend management systems should be explicitly represented in the causal model. A management model is essential when an objective is to predict changes in safety as a result of changes in the way operational and management functions are carried out. The simplest way to model management is by multiplying the probability of occurrence of the top event of the fault tree by a factor which expresses the quality of management. An approach that is more appropriate for the aviation system breaks down the quality of management into different factors, where these factors can individually influence the probability of occurrence of the base events of the fault tree.

The development of a management model requires a development effort that is at least of the same magnitude as the effort needed for the development of the core causal model. Data needs to be generated through audits by experienced audit teams. Many organisations must be audited. Insight into the management factors that influence safety can only be achieved by advanced management models which include adaptive feedback mechanisms. Expanding the core model with a management model will increase acceptance of the model and its results, particularly by the airport authorities. The projects related to the development of a causal model for “internal” safety and Safety Performance Indicators and the experiences of the I-risk study provide a basis for the development of a management model.
The more detail in the core model, the more insight is provided into failure mechanisms, but also the more demand is made on the time available and on the accuracy of the resulting model. With increasing demand on detail in the model, the lack of existing data will become more of a problem. Expert judgement will be needed to fill the gaps. Expansion of the causal tree is limited to the level where common modes occur and the resulting combinatorial explosion of the tree. Common modes at these levels of detail must be linked through an interface to another model, such as a management model.

The advanced modelling is better than the simple for both the core model and the management model, particularly for those concerned with improvement rather than just enforcement, because an advanced model provides more insight into the factors that drive safety.

The aviation system, and in particular aircraft in flight, cannot for all purposes of risk analysis be considered static. Slow changes over time, such as influences from management, maintenance and regulation do not need dynamic modelling. However only rapid changes in time, particularly where several factors vary together (common mode), or where time dependencies are important, do need dynamic modelling. A proper dynamic model will better describe events leading to accidents and enables better modelling of the accident location and accident consequences, including disaster response. Introducing dynamic models however requires significant additional research efforts. It will probably contribute positively to the acceptance of the model, particularly from the airlines.

In summary then, it is suggested that the most feasible approach for the development of a causal model is to divide it into phases. The start is the development of the core causal model, (beginning with a definition study), together with the identification of the functional elements which require more detailed modelling. Parallel to this phase, the possible structure of a management model can be explored which is fitting for the air transport sector with respect to safety. This parallel work provides a greater potential for the interfacing of the two models at a later date and also offers more insight than available from the core model alone. With regard to the functional systems, the two should be compatible. Following on from this, areas for dynamic modelling in both the technical system and the management systems can be identified which will offer greater potential for model improvement in terms of predictive accuracy and reduction of uncertainty. One of the greatest uncertainties of a causal model is in the adaptive behaviour of human and human-technical interactive systems. Just because this is difficult does not mean we should avoid it. It is on the other hand likely that it is in these areas that the greatest payoffs will be achieved rather than in further detailed analysis of the easy to model and known factors. This strand in the development of the total modelling approach should therefore be included right from the beginning. This 3 pronged approach is considered to offer the best opportunity for success in identifying ways to improve safety in the air transport sector, with both short term and long term payoff.
8 References


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