

Further development of a Causal model for Air Transport Safety (CATS); Building the mathematical heart.

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ABSTRACT. The development of the Netherlands international airport Schiphol has been the subject of fierce political debate for several decades. One of the considerations has been the safety of the population living around the airport, the density of which has been and still is growing. In the debate about the acceptability of the risks associated with the air traffic above The Netherlands extensive use has been made of statistical models relating the movement of airplanes to the risks on the ground. Although these models are adequate for the debate and for physical planning around the airport, the need has arisen to gain a more thorough understanding of the accident genesis in air traffic, with the ultimate aim of improving the safety situation in air traffic in general and around Schiphol in particular. To this aim a research effort has started to develop causal models for air traffic risks in the expectation that these will ultimately give the insight needed. The concept was described in an earlier paper. In this paper the backbone of the model and the way Event Sequence Diagrams, Fault-trees and Bayesian Belief nets are linked to form a homogeneous mathematical model suitable as a tool to analyse causal chains and quantify risks is described.

Keywords: Risk, Causal model, Aviation

1 INTRODUCTION

As we described in earlier papers (Ale et al, 2005, Ale et al, 2006), the Netherlands ministry of Transport and Waterworks embarked on a project to model the accident genesis of air transport accidents with the aim of quantifying the risks of air traffic and supporting the development of further measures and methods to reduce these risks and improve safety. The model is being developed by a consortium including Delft University of Technology (TUD), Det Norske Veritas (DNV), National Aerospace Laboratory (NLR), White Queen (WQ) and JPSC consulting.

The original design was based on work done in preparatory projects on air traffic risk estimation (DNV 2002, Roelen et al 2000) and work done in the area of occupational safety, linking technological risks to management influences (Ale et al 1998, Bellamy et al, 1999). This design called for the combination of three modelling techniques in a

single model: Event Sequence Diagrams (ESD), Fault Trees (FT) and Bayesian Belief Nets (BBN).

Since then it has been decided to convert the ESD's and the FT's into BBN's and construct the CATS model as one integrated BBN. This allows using distributions of values rather than point estimates wherever appropriate. It allows a convenient and consistent handling of dependencies and interdependencies throughout the model. It finally takes away the need for artificial transfer points in the model between ESD's, FT's and BBN's.

This however did not take away the need to first develop the ESD's, FT's and BBN's separately as these and their quantification form the basic material on which the integrated CATS BBN is built.

In this paper we use the term accident as defined by ICAO (ICAO, 2002). Usually such an ac-

cident involves the end of a flight, but there are exceptions¹.

2 CAUSALITY

Any effort to construct a model describing chains of causality of events in a system must be based on the assumption that causality exists and that causality even in systems as complex as the aviation industry can be described (ESREL 2007).

Several lines of discussion are continuing. Some of these are triggered by the perceived incomprehensibility of low probability – high consequence events. Some of these by the notion that analysis of causality seems to have no end and some by the more legalistic discussion on whether a probabilistic progression of a sequence of events should lead to a negation of the certainty of the cause after the fact.

The matter of causality is a highly philosophical question. We describe our position with respect to these questions briefly below, in order to justify the continuation of our efforts toward those in the scientific community that have reached the point of seeing no further point in causal analysis and modelling.

The discussion about the infinity of the chain of causality is an old one and goes back to the Greek atomists some 400 years BC (Russell, 1946). The why question in this context can have two meanings: “to what purpose” and “with what cause”. Both questions can only be answered within a bounded system, because they imply that there is something causing the system to exist.

A bounded system can show behaviour that the makers did not anticipate. In most cases the cause of this behaviour can be found as a combination of behaviours of parts of the system that the makers of the system did not consider. Projective analyses take time and effort, and efficiency demands these analyses to be limited. The fact that a behaviour was not anticipated does not imply that anticipation was impossible, merely that it was deemed impractical.

Nevertheless, one could make the claim that complex systems show emergent behaviour that is not only surprising, but could not be anticipated in principle. We agree with Chalmers that this claim is equivalent to proposing that the system is alive (Chalmers, 1996). And although human beings are part of the aviation system we take the position that the aviation system is constructed and run by humans but is in itself inanimate. (Arshinov and Fuchs, 2003, Goldstein, 1999).

As regards causality in the “legal” sense, this is an issue that also plays a role in the discussion about flood defences: what causes a flood: high

water or a low dike. This is a question like what is the contribution of the left hand to the noise when clapping hands. The cause of the flood is the combination of height of water and height of dike where the latter is lower than the former. A cause therefore is a multi-attribute entity. More generally a cause is the occurrence of a particular combination of the values of relevant parameters that give rise to an accident.

Finally there is the notion of probabilistic resonance (Hollnagel, 2006). Resonance implies that the periodicity of one parameter of a system couples with the periodicity of another parameter, leading to synchronisation and amplification of the two. Hollnagel proposes that extremes of random variations of values of parameters combine such that their combined effect brings a system outside its – safe – operating envelope.. In the case of accidents the rare extremes of independent variables occur simultaneously by chance, such as in the – typically Dutch – problem of assessing the possibility and probability of extreme flood conditions. Here the unknown probabilities of extreme values of heights of water have to be deduced from the distribution of more moderate heights. The probability of extreme weaknesses of dikes has to be inferred from the more familiar state of the sea defences. These have to be combined to result in the probability of the simultaneous occurrence of the two, giving rise to a flood. (van Gelder, 2007)

We therefore take the position that causality can be established in the inanimate aviation system in principle. Whether it is worth the effort is a cost-benefit question and therefore profoundly political. In this project we intend to go as far as is necessary to provide decision makers with ways to reduce risk, if they wish to do so.

3 QUANTIFICATION

The question also is raised (ESREL 2007) whether quantified analysis has any use given the paucity of accident data and therefore the residual uncertainty in the final result.

This discussion takes place wherever the risks involving low probability high consequence events have to be managed. (Laheij et al, 2003). In a competitive industry or everywhere else where resources are limited, the ultimate decision is one of cost against benefits. Costs are expressed as a number, be it US dollars, Euro’s or another currency. So in the final decision risk, - with all its complexity – will be reduced to a number. We consider an educated guess, based on carefully designed and constructed models to be better than straight judgement alone. (Ale, 2002; Jongejan et al, 2006)

¹ Such as a passenger having a fall while walking through the aisle, hitting his head and dying.

4 THE EVENT SEQUENCE DIAGRAMS

Accident categories are used to collect similar

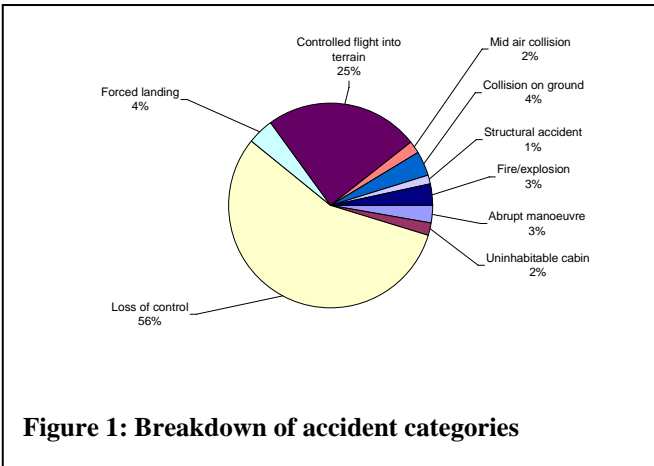


Figure 1: Breakdown of accident categories

types of accidents with similar groups of causal factors together for analysis in one part of the model. The accident categories chosen for the CATS project are defined in the NLR report (Roelen et al, 2000). They are: (1) Abrupt manoeuvre, (2) Uninhabitable cabin environment, (3) Loss of control (unrecovered), (4) Forced landing, (5) Controlled flight into terrain (CFIT), (6) Mid-air collision, (7) Collision on ground, (8) Structural accident and (9) Fire/explosion

The relative importance of each accident category is illustrated in Figure 1, which shows the breakdown of the number of fatal accidents on large Western commercial jets world-wide during 1990-2005. In this dataset, which was constructed from the ADREP database and data supplied by airlines (Roelen et al, 2000), there were 151 fatal accidents causing over 10,000 fatalities. Security events and personal accidents such as falls have been eliminated from the dataset as they are outside the scope of the CATS project. Loss of control and CFIT are clearly the most important accident categories, accounting for approximately 80% of fatal accidents and also for 80% of fatalities.

An Event Sequence Diagram Figure 2 is a flowchart with paths leading to different *end states*. Each path through the flowchart is a scenario. Along each path, *pivotal events* are identified as ei-

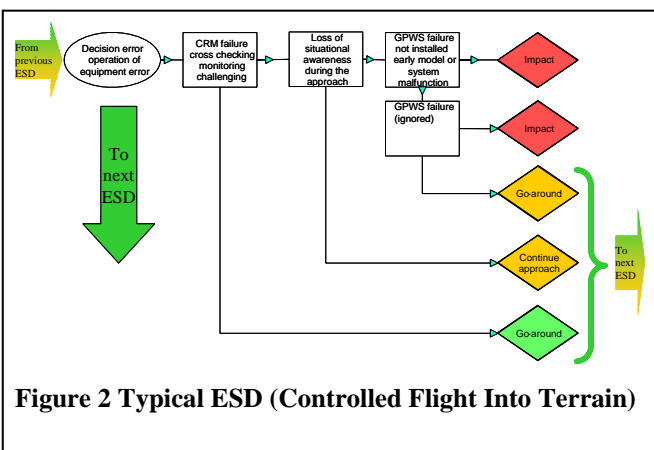


Figure 2 Typical ESD (Controlled Flight Into Terrain)

ther occurring or not occurring. The event sequence starts with an *initiating event* such as a perturbation that requires some kind of response from operators or pilots or one or more systems (Stamatelatos and Apostolakis, 2002).

Conditional operators can be included to represent different outcomes depending on whether the condition is met.

Intentionally, the building blocks of the scenarios are kept broad and generic to cover many 'similar' situations. The detailed specific or possible causes or contributing factors of these events are not directly of interest at the scenario level. They are added, when such details are necessary, through other layers of the model, such as Fault Trees of Bayesian Belief Nets. Event Sequence Diagrams are often combined with fault trees. In practice, Event Sequence Diagrams are typically used to portray progression of events over time, while fault trees best represent the logic corresponding to failure of complex systems (Stamatelatos and Apostolakis 2002). Fault trees are used to model initial and pivotal events in Event Sequence Diagrams in sufficient detail. The initiating and pivotal events in the Event Sequence Diagram are the top events in the fault trees.

Only active events are put in the accident sequence. Latent events are dealt with in the Fault

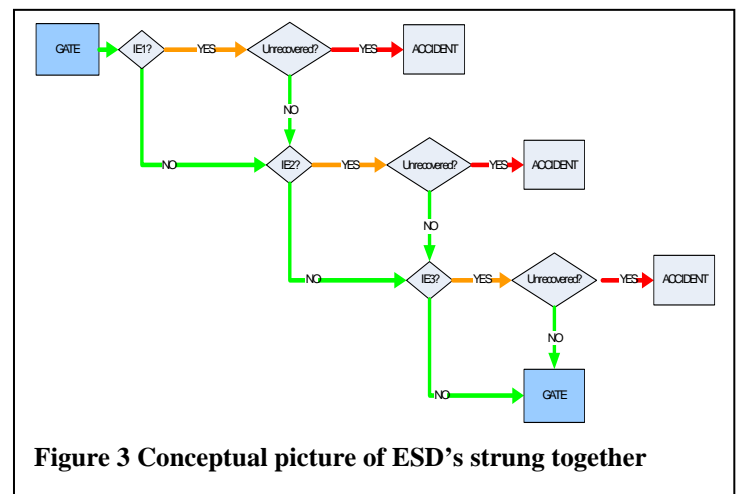


Figure 3 Conceptual picture of ESD's strung together

Trees and Bayesian Belief Nets.

A typical example of an ESD is given in Figure 2, which depicts the ESD for controlled flight into the ground. All ESD's are described in Roelen et al (2006)

The choice of ESD's and the demarcation between them is to a certain extent arbitrary. In any

Table 1: The accident types chosen to build ESD's

| | Taxi | Take-off | Initial Climb | En-route | Approach | Landing |
|---|------|----------|---------------|----------|----------|---------|
| Abrupt manoeuvre | | X | X | X | X | |
| Cabin environment (fire, O ₂) | X | X | X | X | X | X |
| Uncontrolled collision with ground | | X | X | X | X | X |
| Controlled flight into terrain | | | X | X | X | |
| Forced landing | | | | | | X |
| Mid-air collision | | | X | X | X | |
| Collision on ground | X | X | | | | X |
| Structural overload | | X | X | X | X | X |
| Fire/Explosion | X | X | X | X | X | X |

case the demarcation will disappear from a modeling point of view when the ESD's are converted and combined into a single BBN. For the sake of development 35 different accident types are distinguished (Table 1). The demarcation is according to the accident types listed above and the phase of the flight in which such an accident type may occur.

The end states of an ESD can come in three different qualities: (1) The challenge represented by the ESD did not present itself or is overcome and no residue is left: the GREEN state; (2) the challenge was met but some residual problem remains which may influence the outcome in some other ESD in the chain, the ORANGE state (3) the challenge could not be met and an accident occurred, the RED state. Usually getting to the red state means the end of the flight.

The ESD's can now be strung together as conceptually depicted in Figure 3. In this figure every IE means an initiating event of an ESD. In total there are 723 events in the backbone of strung together ESD's.

In work performed for the FAA (Roelen et al, 2006) these ESD's were quantified. This means that the probability of occurrence of the initiating event and the probabilities of the various outcomes were derived from accident data, incident data and the associated movement data (the exposure).

5 FAULT TREES

For each of the nodes in each ESD the probability of going in one of the directions - failure or non-failure - is derived from a fault-tree. Also these fault-trees are constructed and quantified on the basis of accident and incident reports, together with data on the associated number of movements. These are in this stage of the development not very large. In a further development of CATS

more detail could be added, when deeper analyses of causes is deemed necessary and the availability of data allows quantification. An example is given in Figure 4. The AND gates in the fault-trees always have just two feeding entries. This facilitates the interpretation of these AND-gates as barriers in an, equivalent, accident-barrier-target model, which many engineers in the aeronautical world, who will be the typical users of the model find easier to understand. (Visser, 1998; Groeneweg, 1998; Ale, 2006)

As it is the fault-trees where most of the numerical data are supplied to the model, for every number in the fault-tree the source is recorded. This work is still ongoing.

If the data sets used to quantify the fault-trees and the data used to quantify the ESD's were the same, the probabilities calculated through the fault-trees should be equal to those derived in the FAA project (Roelen et 2006) for the ESD nodes direct. However, it is not always possible to use the same data sets. Information about accident precursors must sometimes be extracted from incident databases. These were supplied by airline companies under the condition of confidentiality. Also the ADREP and other databases are sometimes am-

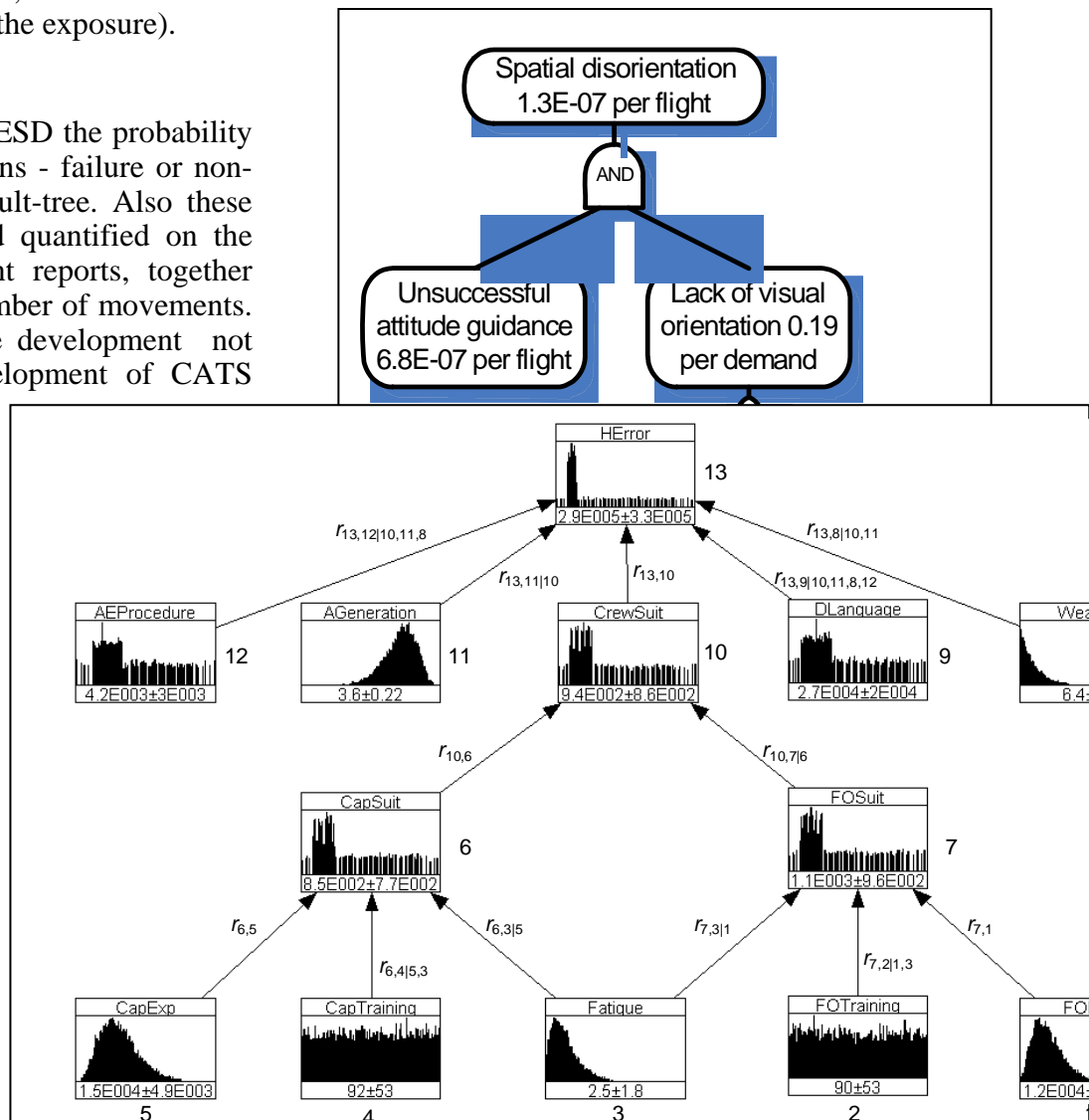


Figure 4: Flight crew performance model quantified

biguous regarding the type of accident. As an example the same accident may be classified as CFIT as well as landing short of the runway. The differences found in numerical outcomes, will be subject of a further paper on the CATS model, once a fuller picture is obtained.

6 THE BBN'S

The human operator plays an essential role at the execution level of any risk bearing activity. In order to account for the influence of the human operator on accident causation, that role must be properly represented in the causal risk model.

Thus, quantified models for human performance are needed. The purpose of the human performance model is to quantify the probability of a human error in certain events in the ESD's and of the Fault trees of the Causal Model for Air Transport Safety. These errors are consistently modelled as the combination of the demand for a certain action and the failure to perform this action.

The original design of CATS called for BBN's mainly when people were involved. Therefore three of these have been envisaged: for a crew member, for maintenance personnel and for an Air

Factors – or variables – that are considered to have a significant influence on the human error probability in the crew and which can be given an operational definition are considered here. Performance shaping factors have been selected after a review of literature and preliminary analysis of a large sample of accidents and incidents). These include training, fatigue, languages spoken, weather, procedures and experience. The crew model is linked to every instance where an action or non action of the crew influences the probability of propagation of the fault through the BBN. In this way, in so far the crew is a common cause these are modelled consistently.

Using a BBN as the modelling vehicle will allow consistent modelling of the interdependencies between events in the model. An example is given below, where there is a dependency between the probability of icing and the probability of engine failure. The probability of this dependency manifesting itself can and will be made conditional on the type of aircraft.

Management influences are modelled using the approached developed in the IRISK project (Bellamy et al, 1999) and modified for CATS as

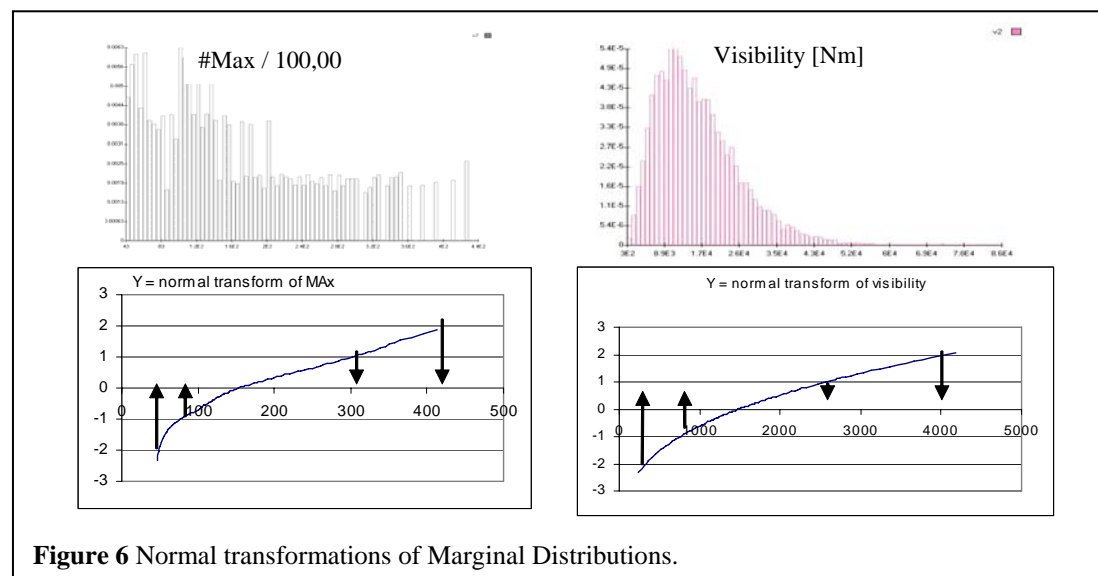


Figure 6 Normal transformations of Marginal Distributions.

Traffic Controller or Air Traffic Manager. The model for Crew is already specified.

The flight crew performance is modelled as a Bayesian Belief Net.

By representing the performance shaping factors in a BBN, we are not limited by the assumption that the Performance Shaping Factors are independent. If necessary, dependencies between performance shaping factors are easily introduced. We propose not to let the specific task determine the (initial) error probability, but to take the associated event in the event sequence diagram or fault tree as the starting point.

Its structure is given in Figure 5, together with the quantification.

described in Ale et al (2006). Although the structure of the model for flight crew error probability is fixed, the value distribution of the parameters can vary depending on the task the crew has to perform.

The values and their distribution are obtained by sessions with experts according to procedure developed by Cooke (1991)

Netica and Uninet software were used to perform the required mathematical operations.

7 CONVERSION TO BBN

A major problem to overcome in the development of CATS was to couple the various modelling techniques. In addition, solutions had to be found not only for the interdependencies inside ESD's,

FT's and BBN's but also between these. Based on experience in previous projects it appeared that BBNs are an attractive modelling tool in which the user readily recognises his problem. The graphical problem representation is also the user interface with which the user can do 'what-if' analyses. BBNs can encapsulate fault-tree Boolean logic, but they can also capture probabilistic rather than strict causal relations. BBNs can also integrate with decision options. The conditional probabilities will either result from data or from expert opinion. There are however also drawbacks using BBN's, especially the discrete versions.

Discrete normal BBNs work well if indeed the normality assumptions hold. If not, then

1. The individual variables must be transformed to normal (requiring of course the marginal distributions).
2. The conditional variance *in normal units* must be constant; the partial regression coefficients apply to the normal units of the transformed variables, not to the original units. This places a heavy burden on any expert elicitation.
3. If a parent node is added, after quantification, then the previously assessed partial regression coefficients must be re-assessed.

To illustrate these issues, the densities for the number of Missed Approach executions per 100,000 flights and of Visibility, as obtained from data for the prototype application are shown in Figure 6. The horizontal units are the natural units of these two variables, and vertical units are the normal units. Normal units are indicated on the horizontal axis as the intervals between the arrow-heads.

In the procedure used in CATS, nodes are associated with arbitrary continuous invertible distributions and arcs with conditional rank correlations, which are realised by the (conditional) copula, indexed by (conditional rank) correlation. (see also Cooke and Bedford 2001)

Use of non-constant conditional copulae would significantly complicate the Monte Carlo sampling and the quantification. The current platform supports only constant conditional copulae, as this is judged prudent for a first implementation. Given that the conditional copulae are constant, there are

great advantages to using the joint normal copulae, which requires constant conditional copulae. Unlike the normal BBN, however, nodes and influences can be added or deleted without re-assessing previously assessed quantities.

The assessment burden for a Distribution Free Continuous BBN is thus one dimensional distribution for each node, and for each arc, a (conditional) rank correlation. These are obtained either from data or from expert judgement.

New protocols have been developed to elicit copulae and influences, one version of which is as follows: Suppose the marginal distributions have already been assessed, or retrieved from data. Suppose Child node C has 2 parent nodes, P1 and P2. Experts are asked, in effect:

What is your probability that C takes a value above the median value of C given the P1 has taken a value above its median

AND

What is your probability that C takes a value above its median, given that both P1 and P2 are above their respective medians.

As the answers to the second question may be constrained by the answer to the first question, real time software support for the elicitation is required. The probabilities given in response to these questions can be converted into conditional rank correlations using the normal copula.

8 FROM FAULT-TREES TO BBN'S

The method developed for CATS translates a fault-tree into the equivalent BBN. This BBN is special in the sense that any node can only take two values and that the state of downstream nodes is completely determined by Boolean combinations of the upstream nodes. (in fact a fault-tree). By translating a fault-tree in this way Fault-trees and BBNs are just parts of a larger BBN and can be treated and quantified in a single operation In Figure 7 it is depicted how the fault-tree of Figure 4 is transformed into a BBN. If the FT contains no repeated events, then its basic events may be assigned distributions, reflecting uncertainty in the probability of occurrence of the basic events.

It may be slightly cumbersome to rewrite a fault tree to the corresponding Bayesian belief net. Moreover one cannot see from the BBN graph to which gate a given influence corresponds. This information must be retrieved from a conditional probability table. On the other hand we can easily see an influence of each gate on the top event as all intermediate failure probabilities of each gate are calculated.

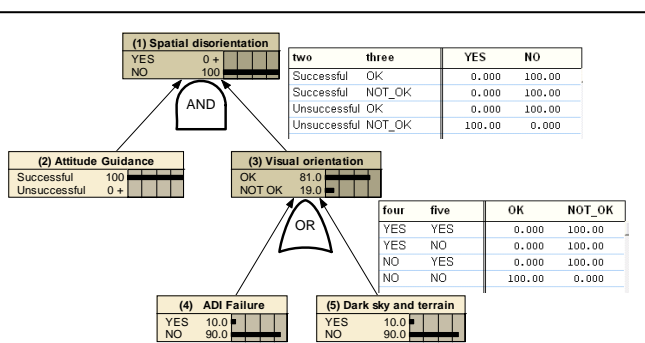


Figure 7: From Fault tree to BBN

The main difference between the FT and BBN approaches is that a FT represents a binary function with basic events as inputs and the top event as the output. BBNs however represent a joint dis-

tribution between binary random variables (basic, intermediate events and the top event). Hence BBN is a much richer model than FT and will allow the existence of repeated events as well as dependencies between events.

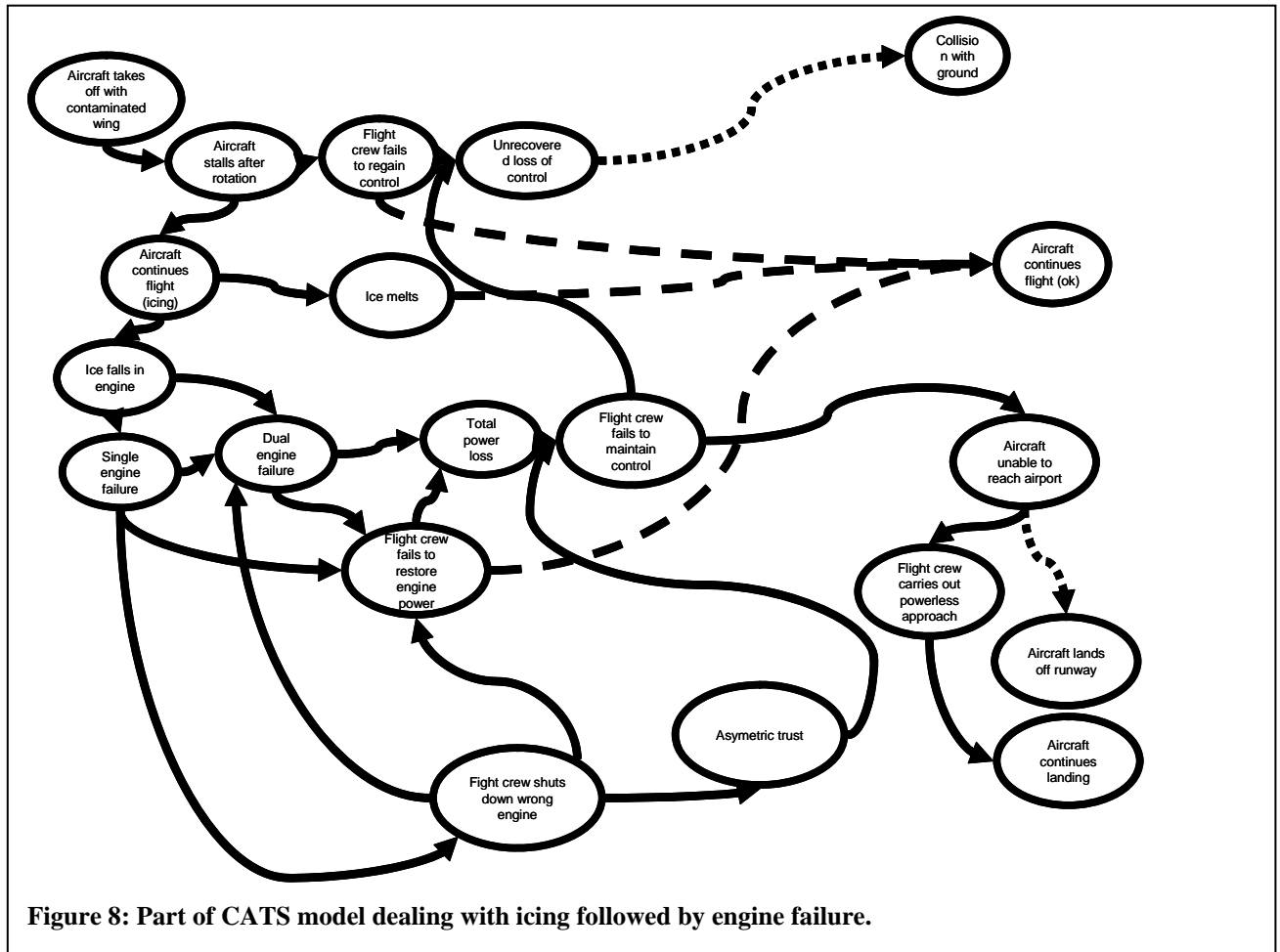


Figure 8: Part of CATS model dealing with icing followed by engine failure.

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The conversion of ESD's to BBN's is straight forward as they already are directional graphs of which the conditional probabilities of the nodes and the arcs are known.

9 INTEGRATED BBN

The whole model can now be integrated in one single BBN.

The section of the model shown in Figure 8 is dealing with the ESD for icing and the ESD for engine failure.

The ESD for icing involves in essence a take-off with contaminated wings (icing), which can lead to the aircraft stalling and the crew losing control at take-off.

If the crew manages to take off successfully the ice may come loose. On an airplane having two tail mounted jet engines (such as a DC9) the ice may enter the engines leading to engine failure on one or both of the engines (FSF 1993).

Therefore there are direct causes for engine failure and causes originating in other ESD's or hazards which only partly have been overcome. Figure 8 shows the various pathways leading to complete loss of power. The dashed lines are pathways leading to other sections of the model in an orange state. As described earlier this means that there are faults remaining in the condition of the aircraft which may lead to increased vulnerability of other mishaps. In model terms: to increased probability of other failures.

10 VALIDATION

In this stage of development no definitive validation can be performed. In any case validation will only be possible to the extent that changes in safety performance of the past resulting from design decisions in the past are calculated correctly. Once this validation has been done, the model will be used first as an additional input to safety decisions in the Netherlands aerospace industries. It took about 20 years between the conception of a causal model for chemical plants and the introduction in the legal system in the Netherlands (Ale, 2003). A similar cautious introduction of these sort

of techniques in the Air Traffic industry should be expected

11 CONCLUSION

The structure and backbone of a Causal Model of Air Traffic Safety has been developed. The backbone consists of the string of 35 separate accident categories with repetitions in each flight phase, which are based on a study of accidents and incidents over 2 decades. The probabilities of the various accidents pathways are quantified using first fault-trees developed from accidents and incident reports. A model for the error probability of crew members has been developed and quantified using expert judgement elicitation techniques. The model is integrated in a single integrated Bayesian Belief Net, which allows consistent handling of probabilities and their interdependence

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