Using a Causal model for Air Transport Safety (CATS) for the evaluation of alternatives.

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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 is underway to develop causal models for air traffic risks in the expectation that these will ultimately give the insight needed. In earlier papers we described the model, the underlying concepts and the mathematical principles used in building the model. In this paper the complete model is briefly described and a few examples are given of the use of this model in comparing the risk of alternative solutions for airtraffic problems in and over the Netherlands.

Keywords: Risk, Causal model, Aviation

DNV, London, England

1 INTRODUCTION

Third party risks of air transport have been a subject of political debate in the Netherlands ever since the crash of a Boeing 747 into an apartment building in one of the densely populated suburbs of Amsterdam in 1992 (Ale and Piers, 2000). This has lead to a continuous effort in developing and improving the understanding of these accidents. Originally these efforts were aimed at developing models to describe the probability and consequences of crashes based on statistical evaluation of similar accidents in the past. Such modelling is very limited in its ability to investigate and evaluate actions to reduce the probability of these accidents.

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 (Ale et.al, 2005, 2006). 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, Papazoglou et al, 2002, 2003, 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).

In Ale et al (2007) we described how the the ESDs and the FTs were converted into BBNs, enabling the construction of the CATS model as one integrated BBN. This allows the use of distributions of values rather than point estimates wherever appropriate. It also 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 ESDs, FTs and BBNs.

In this paper we use the term accident as defined by ICAO (ICAO, 2002). Usually such an accident involves the end of a flight, but there are exceptions, such as a passenger having a fall while walking trough the aisle, hitting his head and subsequently dying.

As the model in principle was described in the the papers (loc cit). The uncertainties wer described in Ale (2008). In this paper we address particularly the advantages of using BBN as a modelling tool and we give examples of the application of the model.

2 THE MODEL CONSTITUENTS

The Causal model for Air Transport Safety (CATS) integrates models for technical failures such as event sequence diagrams, fault trees, event trees and models for human behaviour in a single BBN.

All potential accidents are divided into accident categories,.which collect similar types of accidents with similar groups of causal factors 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 failure and (9) Fire/explosion. These Event Sequences form the “backbone” of the model development. For each phase in a journey – taxi, take-off, en route, approach, landing and taxi – these categories of accidents are developed in event sequences, as preparation for inclusion into the BBN. The events in the event sequences are the broad parts of accident scenarios such as the loss of control or the decision to abort a take-off.

Each event is defined such that it can go in only two directions. The probability of going in either direction is determined by the outcome of a fault- tree. For each event in each of the event sequences, a separate fault tree is developed. In this stage of building the model, states could only be failed or not failed. However later, when the fault-trees are converted to elements of the BBN multiple (degraded) states were allowed and the Boolean logic was replaced by the probabilistic relationships which are used in the BBN wherever necessary.

Where humans are involved in fault development then models for human operators are attached. In the current CATS models are being developed for three types of human operators: Pilots forming a crew, Air Traffic Controllers forming Air Traffic Management and Mechanics performing maintenance.

Many of the model elements are repeated. For instance, although the pilots remain the same during the flight, they may be tired at the end of the journey. The weather could be different for the two ends of the flight. Separate instances of the pilot model, of the weather influence and parameters associated with airports are used when required.

The resulting BBN is partially depicted in Figure 4. The final outcome is the probability of an accident. In this BBN the interdependencies between different sections of the model, such as the relationship between engine failure, fuel starvation and go-around manoeuvres are already introduced. Here the real power of using a BBN over the event and fault trees starts to manifest itself. The effects of interdependencies on the final result can be modelled directly.

No less useful is the fact that the states of the nodes can be distributed over many values and that this distribution can be continuous rather than discrete and that the edges of the BBN are – conditional – probabilities as will be shown later.

3 DATA.

A model such as CATS has large data requirements, the major problem being the exposure data. It is not sufficient to know how many failures of a certain piece of equipment are recorded in an accident database. It is necessary to also know how many failures of that same instrument occurred without an accident and in how many flights the equipment did not fail at all.

Data are gathered from ICAOs ADREP database (ICAO, 2002), from data made available by airlines and by airports. In addition work is underway to use data from the Line Operation Safety Audit (LOSA) database (ICAO, 2002a; Lin, 2008) to establish the performance of pilots with and without accidents. If the performance was – in part- influenced by the equipment or by circumstances these underlying causes were taken into the model whenever possible.

For each number in the model, the uncertainty in the estimate was expressed by a standard deviation. The estimate and the standard deviation are used in the BBN to define the distribution of values or probabilities in the nodes of the BBN.

When no data could be found, expert judgement was employed. For this the method developed by Cooke et al (EUR 18820, 2000) was employed to maximise the chance of unbiased estimates.

For several entities in the model proxy entities needed to be established. For instance it is generally understood that pilot training is important, but a definition of what a well trained pilot means is lacking. In CATS we use the days since last recurrence training as a measure for training. The correlation between this number of days and the pilots proficiency in handling aircraft and emergencies is developed from the data and from expert opinion sessions with pilots and instructors. These correlations were obtained in a way presented in Morales et.al. 2007.

For the development of CATS in all a few thousand numbers needed to be extracted or estimated. The origin and a characterisation of the quality of the data are held in a separate database. This not only helps future users of CATS in interpreting the results of an analysis, but also forms a basis for recording data in the future. By targeted recording, weaknesses and holes in the data structure can gradually be remedied.

4 MAPPING OF VARIABLES

As was mentioned above, the model was developed top down. From a set of typical accidents down to base events. The development was

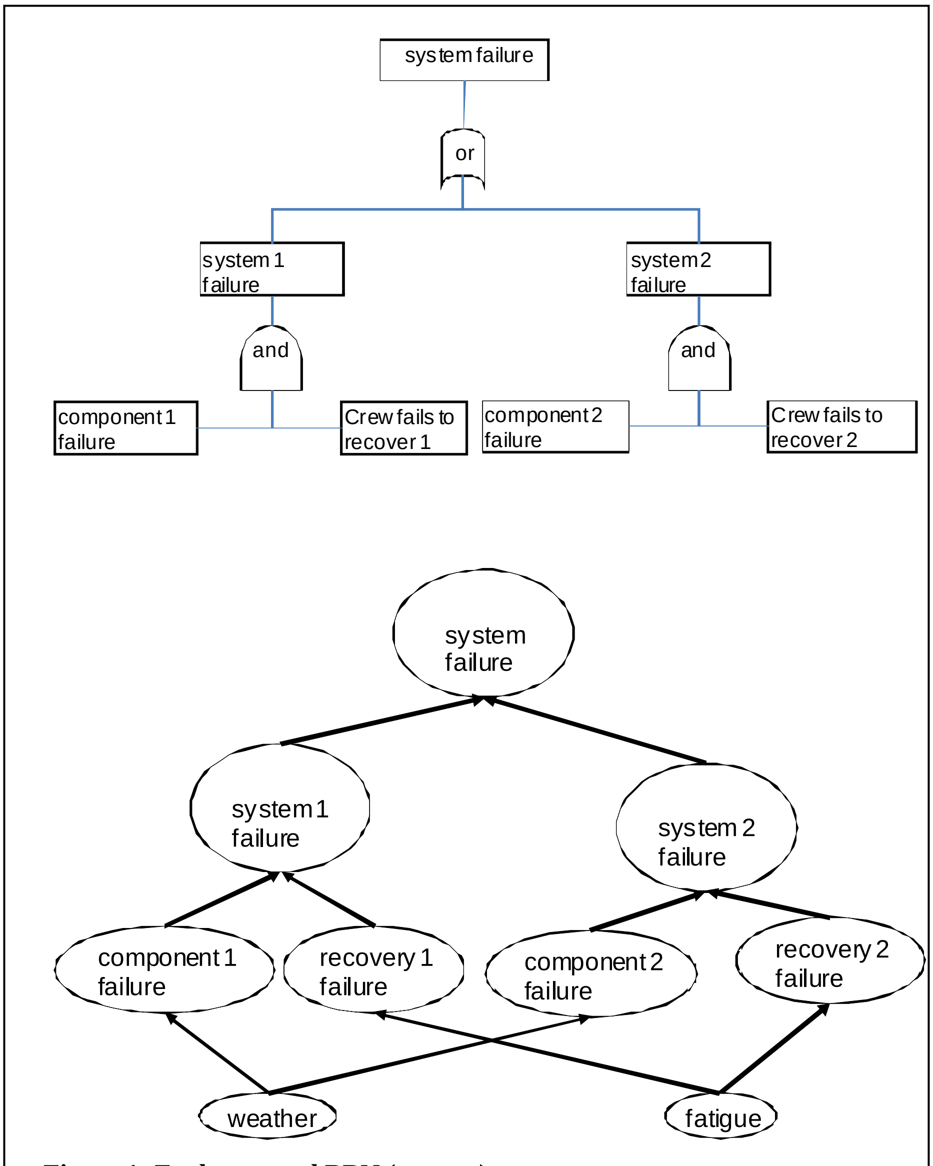

Figure 1: Fault-tree and BBN (see text)

stopped at point where it was judged to be doable to develop probability numbers from either data or expert judgement.

In many cases however this is not the way air traffic experts actually look at the air traffic system. They use in many cases aggregate notions such as the complexity of an airport, the complexity of airspace, good or adverse runway conditions and aircraft generation. These notions translate into changes in probabilities of many of the model constituents. Therefore a translation or mapping has to be made of the variables or notions common in the industry and the base events of the BBN.

For instance runway condition influences the probability of incorrect application of brakes. In the ADREO database there is no definition of bas or good runway conditions. Instead it is reported whether it rained at the time of the accident Therefor in the database rain is a proxy for bad runway conditions.

In the expert judgement exercise it is subsequently asked to what extent the probability of incorrect brake application would increase under adverse runway conditions.

In CATS the estimates from experts and the estimates from data are brought together in one system. Calculations are performed to establish a consistent picture between all the “known” quantities in the BBN by adjusting the “unknown” quantities.

In the course of the development and testing several occasions have been identified where the total of the information is inconsistent. For instance experts expect an increase in probability of incorrect handling of the brakes on landing – all other remaining equal – under wet runway conditions of a factor of 10. The accident data suggest a factor of 7. Although it may seem that the difference is small and that an order of magnitude is an acceptable expert representation of a factor of 7, it should be realized that a fault sequence may have many of these steps, especially if management factors are taken into account. When there are a number of these differences in a single chain, the resulting estimate of the probability may exceed the maximum derived from the data. This may be caused by the uncertainty in the data or by the uncertainty in the estimate by the experts. The discrepancy between what experts expect of certain conditions or measures and what really can be achieved may also be orders of magnitude. If the data are “real” and when decisions are made on the basis of expert judgments, which is often the case in the absence of quantified models, the expectations of safety measures, including those in the realm of resilience may be grossly overstated.

In this stage of our investigation this issue has to remain unsolved. In the next stage of the development CATS will be used to explore discrepancies between expectations, judgments and reported facts. The latter of these three is just as an issue as the former two. As we have reported earlier, there are many inconsistencies in the available data. Therefore it may be necessary to set up a program to observe a number of key parameters over time. This will give a better assessment of the real probabilities of underlying events.

Even when the model is kept relatively simple there are many layers in the model when safety management systems are taken into account. Differences of a factor of 1.5 build up quickly to orders of magnitude. This may be seen as an argument against quantitative modelling as the accuracy of these models then cannot be better that orders of magnitude. It should be borne in mind though that the estimates of experts are equally loaded with uncertainties. The currently dominant way of making decisions on the cost effectiveness of investments in safety, safety measures and safety management is mainly based on expert opinion. The deception in time that measures did not bring what was expected is the unavoidable result, if these opinions consistently overestimate effects of change.

5 ADVANTAGES OF USING BAYESIAN BELIEF NETS

Using Bayesian Belief Nets as the modelling vehicle has several advantages over using fault trees and event trees.

First of all in BBNs the events do not have to be linked deterministically as in the trees. In trees the state of an event can only be a binary quantity: yes of no, true of false. This state is completely determined by the states of the events lower in the tree and the logic of the gates that connect them. Therefore, once the states of the base events have been defined, the state of the top event is known. If probabilities are assigned to the states of the base events, the probability of the corresponding state of the top event is the result of a straightforward but often computationally expensive calculation . In particular, if there are repeated events in the FT then Boolean reduction must be applied before substituting probabilities for Boolean variables. Uncertainty analysis with fault trees is performed by sampling probabilities from the distributions of base events, in order to obtain a distribution of probabilities of the top event. Dependencies between the probabilities of occurrence of base events must be captured outside the fault tree.

BBNs support both functional and probabilistic nodes. Roughly, this means that they can capture all functional relations within a fault tree and also dependences between probabilities of occurrence of base events. If a fault tree is used with Boolean variables, then a BBN representation represents the gates as Boolean functional nodes. Repeated events are represented as functional identities. If Boolean reduction has been applied and the fault tree is in a form suitable for substituting probabilities, then the transcription to a BBN is straightforward. In either case, dependencies between nodes can be modelled within the BBN.

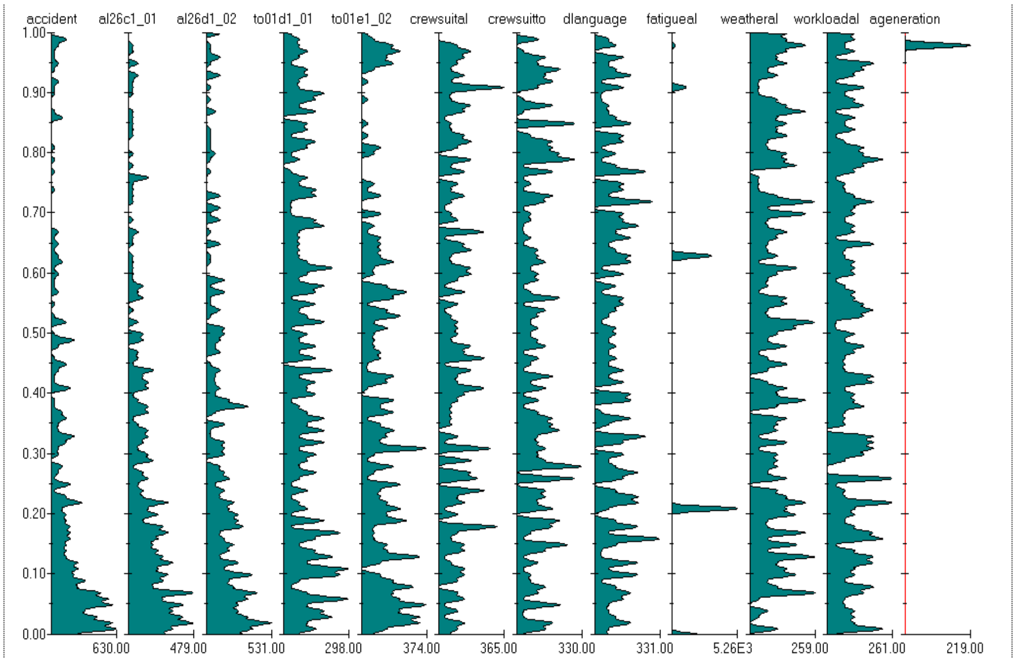

Figure 2: Importance estimation

These advantages come at a price, however. Whereas the fault tree shows the type of relation between events as an AND gate or OR gate, etc., the BBN merely shows that there is some relationship. One has to open the BBN and go inside to see the type of relation. (Figure 1)

Many studies struggle with the explanation of rare events or accidents that seem to be almost extraneous to the system at hand. The problem of explaining accidents and incidents in high reliability organizations has led to many metaphors such as the functional resonance metaphor by Hollnagel (2006). In these organisations it is often the combination of extreme values of parameters that is the cause of an accident. In a model using

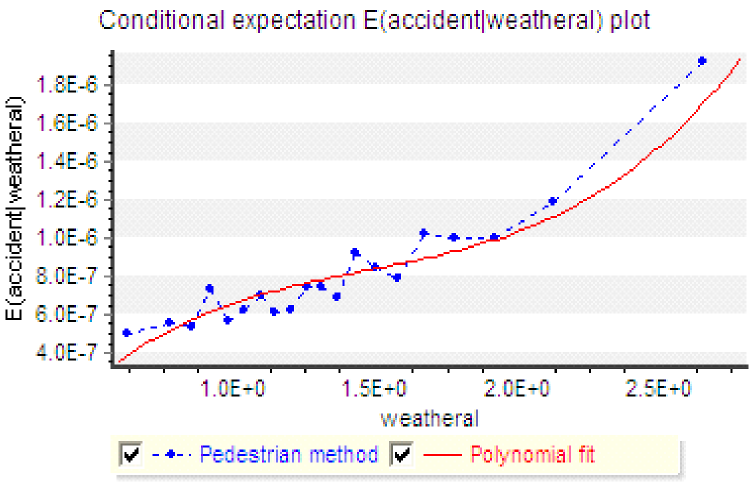

Figure 3: Sensitivity analysis

BBN's the distribution of values of parameters can be explicitly taken into account. Therefore it is exactly this behaviour of the model that makes it particularly suitable for the analysis of accident causation. Unfortunately it also makes the model less intuitive to use. More than in tree models the analyst has to ask herself whether she uses the model correctly given the question being asked.

6 INITIAL ANALYSES

In the example given in Figure 2, the distribution of accident probability and the distributions of a number of underlying factors is given in the case the aircraft generation is set to the most recent: generation 4. It can be seen that generation 4 aircraft mainly are involved in accidents with a low probability. This is not the same as the statistical fact that generation 4 aircraft have a lower accident rate than the older generations of aircraft. Not only have generation 4 aircraft a smaller accident ratio, if they are involved in an accident it is more likely to be an accident of a rare or unusual or unexpected type. This re-inforces the rationale behind the development of CATS. It is indeed necessary to look at the more extreme values within the design range to detect combinations that will promote or even cause an accident.

In another analysis the correlation of accident probability and weather resulted in the relationship between accident probability given a certain state of the weather and the weather. From the graph depicted in Figure 3 it can be seen that the weather is indeed the dominant factor influencing accident probability. This is not a surprising or new result, but confirms that the model functions correctly in those cases for which the answer is "known". It is also a sobering conclusion. Accident probability is dominantly influenced by a factor over which we do not have any other than stay out of the bad conditions..

7 EXAMPLE

The example presented builds on this notion. In particular we looked at the calculated difference between landings at crosswinds below 15 knots and above 15 knots.

The speed of crosswind is a proxy for what the general pubic would characterise as lousy weather. Around Schiphol airport two situations with high crosswinds can be distinguished. One is a steady storm with a component perpendicular to the runway in use, and the other is unstable gusty wind with locally highly variable wind speeds and directions. In the latter situation the weather reports sent to the pilot usually are not capable of stating precisely what the wind will be at the runway during the few minutes that the airplane will be on the runway to complete its landing roll.

For Schiphol, crosswind – or bad weather – is of particular importance. Bad weather is usually associated with high gusty winds predominantly from the West, while the direction of the runway system is predominantly North-South. Only one of the runways has an East-West orientation (09-27). When the weather forces the airport to use this East-West runway only, the capacity is greatly restricted. Furthermore it is this runway that the unfortunate flight in 1992 tried to approach when it crashed on the city. Both from an operational point of view and from a political point of view it is important to avoid use of this runway. ICAO rules demand 15 knots as the limit for runway assignement.

At night runway 09-27 is closed. This means that the airport is essentially closed when the crosswind exceeds the set limit. An aircraft veered off runway 19R on December 24th, 1997, while attempting to land with an actual crosswind of up to 35 knots. Runway 24, which would have resulted in a practically negligible crosswind component as the wind direction was 240º, was closed as it was close to midnight (and Christmas eve as well). The accident investigation board identified as a causal factor of the accident: "The runway allocation system at Schiphol Airport resulted in strong crosswind conditions for the landing runway in use". [RvTV 1999]

It would be desirable if this limit could be relaxed without compromising safety.

Table 1 relative probabilities of runway veeroff

		RUNWAY	
		DRY	WET
WIND	less 15 kts	1	400
	more 15 kts	15	400

In this paper we address one of the scenario's associated with bad weather: runway veer of.

The model does not reveal any specific technical issue associated with bad weather conditions when on the ground. Two issues can be identified: the handling of the airplane during the landing roll and the way a thrust reverser failure is handled. From the data and from the expert opinions underlying the quantification of the crew behaviour model it can be derived that the probability of inappropriate handling of the aircraft and of the thrust reverser failure is more problematic during bad weather as during moderate weather. When the probability of a veer off during moderate weather is set to 1, table 1 gives the relative probabilities of the other event/circumstance combinations. It can be seen that the probability of leaving the runway in a veer off is more than two orders of magnitude larger under weather conditions with high crosswinds and rain. However, a wet runway seems to be a much larger influence than crosswind. Hence the difference between low or high crosswinds cannot be seen when the runway is wet.. The next step in the analysis will be to investigate to what extent this is caused by the extremes of the distribution of wind speeds associated with bad weather and rain. If indeed this is caused by the high end of the spectrum, a more accurate and timely warning of the actual wind speeds on the ground may solve this problem for much higher average cross winds, and enable Schiphol to use its runways to capacity in worse weather than currently is safely possible.

8 VALIDATION

Validation of the CATS model 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. The available data are barely enough to populate the model with the required initial set. Independent quantitative validation is impossible. Therefore other approaches will be used to maximize the validity of the model, such as comparison with other existing models, expert and peer review on the equations, probabilities and distributions used. 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 sorts of techniques in the Air Traffic industry should be expected

The BBN structure also allows analysis of the correlation of accidents with the underlying causes. As was discussed earlier, in a system with a highly reliable system such as the airtraffic system there are not many accidents for which a single defined cause can be established. Correlation analysis may give a lead to combinations of more extreme values of parameters is the system, that could cause an accident. A system was developed which displays the distributions of parameters associated with a certain selection of values of other parameters or variables.

9 CONCLUSION

The work that started three years ago resulted in a single Bayesian Belief Net structure to describe the probability of an air traffic accident. The first applications indicate that the model functions correctly and produces results that are in accordance with observations and expert insight.

However CATS or similar quantitative methods, which bring together reports, observations, facts, opions, judgements and expectations can help to improve our insight into what can make air traffic safer. It also suggests a pathway to a further development of methodology in other strands of quantified risk analysis.

Expected and unexpected outcomes will need to be carefully evaluated in the next period to gain confidence in this new way of building a causal model. For the time being the results and performance of the model exceed the initial expectations.

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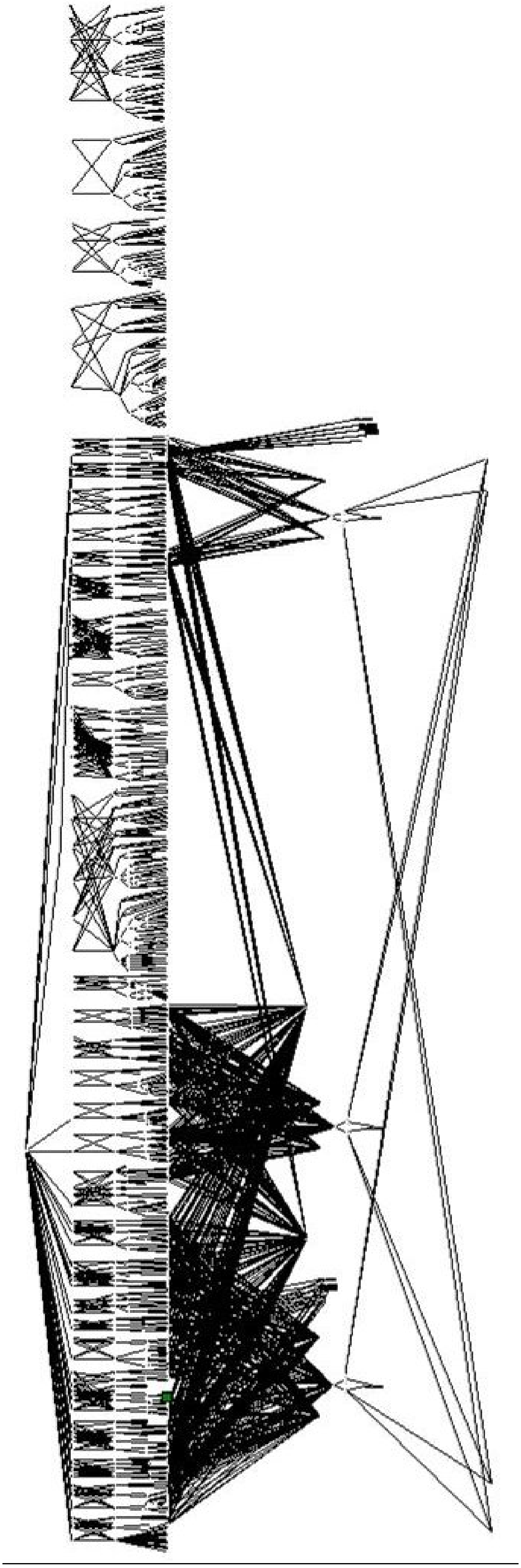

Figure 4: The CATS BBN

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