Modelling risk in high hazard operations: integrating technical, organisational and cultural factors

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Abstract: Recent disasters in high hazard industries such as Oil and Gas Exploration (The Deepwater Horizon) and Petrochemical production (Texas City) have been found to have causes that range from direct technical failures through organizational shortcomings right up to weak regulation and inappropriate company cultures. Risk models have generally concentrated upon technical failures, which are easier to construct and for which there is more concrete data. The primary causes, as identified by the US Chemical Safety Board for Texas City and the Presidential Commission for the Deepwater Horizon, lie firmly rooted in the culture of the organization and determine the way in which individuals go about risky activities. Modelling human activities, especially collectively rather than individual human errors as is done in most human models, is a quite different proposition, in which complex interactions between different individuals and levels change over time as success and failure alter the pattern of payoffs.

This paper examines the development of an integrated model for risk in a real-time environment for the hydrocarbon industry. It is based originally on the CATS model for commercial aviation safety, that first attempted to address some of these problems in a relatively simple way. Aviation is, however, a relatively simple activity, with large numbers of common components in a constrained environment. The Oil and Gas industry is significantly more diverse, covering the gamut from exploration, drilling, production, transport, refining and chemical production, each with its own potential for large scale disaster, but in the case of an integrated oil company all run by individuals within a common company culture. Other papers will cover the details of specific issues; this paper covers the integration of the model as a whole.

Keywords: Risk management, Bayesian Belief Net, Major Hazards, Human behaviour.

1. INTRODUCTION

In this report we describe the proof of concept for a risk management support tool. This method should enhance the methodologies currently employed by the company and in particular allow the evaluation of the present and future vulnerabilities to catastrophic events. It also should allow the evaluation of the potential effect of actions – by management or by authorities – on these vulnerabilities. The development of such a model employs the latest in the development of the sciences of risk analysis, mathematics and human behaviour. The approach chosen is therefore innovative in all these respects.

1.1. History

The recent blow-out and subsequent environmental disaster in the Gulf of Mexico have highlighted a number of serious problems in scientific thinking about safety. One of these is that our current thinking about how accidents happen and all the management systems based on that approach, while reasonably successful, does not appear to enable us to achieve the goal of zero accidents. These are particularly clear in the case of what can be described as low-probability high-consequence accidents which, while quite rare, do not really appear to be reducing in frequency unlike simpler and higher frequency personal accidents (Christou, 2008), while their consequences appear to increase. The suggestion is that linear and deterministic models of accident causation are insufficient to catch the residual factors and their interactions (Hudson, 2010). This is further complicated by the fact that the safety culture can either augment or diminish the effects of the best of HSE management systems. The latter appears to be the case for BP's Deepwater Horizon disaster, which was then exacerbated by a poorly managed emergency response, or, at least, the perception of poor response. A deeper and wider-reaching analysis of the risks being taken and run needs to integrate the cultural and regulatory factors into the more accessible technical aspects of risk analysis and assessment.

Recent proposals have suggested that systems such as the current process industry and the world financial system have become so complex and the interactions so manifold that these systems become intractable, and therefor unmanageable. Accident causation must be regarded as both non-linear and non-deterministic (Hudson, 2010). Simple models, that are linear and deterministic, suffice to approximate to a level that may have been acceptable in previous years, but, as Hollnagel (2011) pointed out, they cannot meet the law of requisite variety (Ashby 1956), which means that control systems need to be capable of at least as much variation as the body to control. The Swiss Cheese model, developed as Tripod in the 80's and early 90's, is an example of a more complex model that is no longer necessarily linear, but is still deterministic in its thinking about accident causation and the approaches to safety management it implies. It appears that a more comprehensive description of the accident process now requires a shift from the simpler models based on the principles of hazard – barrier – target concept (Schupp et al, 2004), possibly including failure rates but still deterministic, to inherently probabilistic models.

The current project addresses these issues and thereby supports the vague notion of " Chronic Unease" current in the company with more concrete information, as this unease is the logical consequence of the combination of "Goal Zero" and the non-zero probability of an accident which has to be accepted given the technical boundary conditions and economic constraints. The approach used in this paper is especially suited to the low probability, high consequence events that form the ground for this chronic unease (Beddington, 2011).

Another reason proposed for the failure to achieve a zero rate of accidents within high-hazard operations has been the safety culture of those involved. However, while there have been many studies of what might constitute a safety culture, there has been little or no study into how the safety culture and governmental regulation actually interact with technical and procedural controls to ensure safe operation.

1.2. Indicators

Management practices increasingly rely on the observation, monitoring and steering by way of indicators. Here it is assumed that these indicators present a true picture of the system under control and cover all relevant issues to be taken into account. There is a continued discussion on what a sufficient and comprehensive set of indicators or KPI's should be. There are three major problems with indicators:

1. Indicators have to be evaluated from historical data. For management they have to serve the purpose of predicting where the system is going with or without management actions. Given that most safety related indicators are probabilistic in nature, only a probabilistic prediction can be made as to where the indicator might go. This in turn makes it difficult to prove or disprove that the expectations have been met; that the action has been a success or even that the prediction itself is correct. This is especially true if the indicator is a number of observed events and the intrinsic probability of the event is low. As an example, consider a manager who is in charge of a site for 5 years and that the probability of a major catastrophe on the site is one in a thousand years. The probability that this event will occur during his reign is less than half of a percent. This means that it is unlikely for him to physically see the effect of any management action he will take to reduce the vulnerability, whether this is for the better or for the worse.

2. Indicators are used as performance measures not only of the system, but also of the quality of the managers. The pay of the managers in part depends on this quality. For this the indicators need to be readily measurable and visibly under the control of the manager. This invokes strategic behaviour, in which efforts are directed to improve the indicator regardless whether the system is improving. In this way indicators, can quickly lose their value, just as any statistical indicator when used for control purposes (Goodhart, 1975). In this respect, the behaviour of KPI's is subject to similar behaviour as physical systems (Heisenberg, 1927).

3. Indicators need to be observable. This may lead to a situation in which important parameters that are not easy observable remain out of the indicators. Especially when these observables are slow to vary such as the probability of a major event. The result is that the probability of a major event is no longer considered important and management loses sight on significant vulnerabilities, of which the probability may be low, but the consequences catastrophic.

The use of Risk Matrices in which the probability of major events is depicted explicitly only in part solves these problems primarily because these matrices are more difficult to interpret. Managers tend to prefer single number and single dimensional indicators over two dimensional multiple number diagrams, in which the weighting between interests of which the magnitude and the probability may differ by orders of magnitude has not been made already. Nevertheless, recent events in the oil industry (Deepwater Horizon) as well as in de financial business (Lehman Brothers) have shown that both ends of the spectrum: high probability-low consequence on the one end and low probability-high consequence on the other need to be kept under observation and that merging the two is unwise especially when the consequences of the low probability events may lead to ruin. Therefore, it is essential that state of the art concepts and methodologies in safety science are translated into indicators and language that is meaningful in the practical context of managing occupational and process risks in a complicated industrial environment. A study into the potential of using market capitalisation as a measure of vulnerability is reported in a separate paper (Gulijk et al, 2012).

1.3. The purpose

The purpose of the project is to show that it is indeed possible to observe the vulnerability of a company in a meaningful way also when the events of interest differ by orders of magnitude in probability as well as in consequence. These observations can then be used to steer management towards not only controlling the short term risks, for which the reward is immediately visible, but also the rare disasters that individual managers are unlikely to see in their term in office, but may ruin the company as a whole.

The challenge in the project is to harness general scientific knowledge, worldwide industry data and company specific experience and exploit the combination to develop a picture of current vulnerabilities and sensible ways to influence them. This picture should give a clearer sight on parameters that vary slowly over time and for which fast indicators are virtually useless. The slow decay of material may be one of these, but much more important and much less tangible are the slow changes in the behaviour of the workforce, from top management to work floor operators, due to societal and economic changes and the psychological structure of human beings. Humans adapt easily to slow changes which are the implication of life. Growing older and changing circumstances are absorbed in the normality of daily life and form the background of the quick pace of industrial production and management of finances. These changes go unnoticed until, often suddenly, a technology proves obsolete, a system fails, humans find themselves an anachronism in the changed society. In case of a catastrophic loss, these are the changes that end up in the post-mortem report. And these are the changes that the current project is after to identify in time.

The object of the study is a chemical plant in the Netherlands. In this proof of concept study only three operations will be studied in detail: the hydrogenation reactor, a storage tank and a loading arm. These are taken as “proxies” for the whole of the plant. These operations differ sufficiently to show that when the methodology can be developed for these three operations it can be done for any operation in the companies “downstream” facilities. A further study will be done in the “upstream” facilities in the continuation of this project.

2. AIM OF THE PROJECT

The project is a proof of concept. It builds on previous work and developments. Therefor there are concepts and methods for which a further proof is necessary and there are concepts and methods that are so well established that they need not to be considered explicitly in this project, even when they will be part of the ultimate method.

2.1. Established technology

The technology of classical quantified risk assessment is well established and is part of the daily practices in the petrochemical industry. Calculation of the consequences and damage resulting from a release of hydrocarbons or other chemicals from the installations is necessary to develop a complete picture of the risk. In this project we have chosen to only sketch these consequences in a rough form. For this proof of concept it is not necessary to have a precise estimate. In a later stage consequence and damage models can be more precisely introduced when necessary.

Similarly, the estimates of average failure probabilities are taken form standard handbooks (Ale & Uitdehaag, 1999). As was already said, only three separate operations are taken to represent all of the Moerdijk plant. For these the estimates made in analyses by the company experts were taken as the starting point. The occupational risk estimates were based on Dutch national data assembled during the WORM-II project.

2.2 New developments

The current development builds on the earlier developments in the IRISK, ORM and CATS projects to connect the descriptions of management, human behaviour and technology into a single framework that allows a more in-depth analysis of the interdependencies. Probability *distributions*, rather than simple bifurcations, are used to take account of the wide range of context-dependent factors that can ultimately result in disaster or, alternatively, providing knowledge essential to take risks and run them successfully and profitably. A number of questions centred on how useable complex probability distribution information can be gained, validated and then used by more than just technical specialists. This novel approach to probabilistic models, Bayesian Belief Networks, has already been successfully applied in civil aviation and developed into a rigorous framework capable of being applied to other high-hazard industries such as petrochemicals and shipping. By doing so a different approach to uncertainty in complex systems is taken, an area where conventional risk thinking, as applied in finance markets for example, has been signally found wanting solutions for situations when the individual probabilities become very small, but the consequences have been found to be out of proportion.

To develop the human behaviour model the overall context has been examined within which risks are taken by organizations given a license to operate by regulatory bodies. Many recent disasters, such as NASA’s loss of both the Challenger and Columbia space shuttles, BP’s Texas City and Deepwater Horizon, and the Global Financial Crisis, can be seen with the benefit of hindsight as caused ultimately by organizational cultures operating at, and over, the edge with permission granted by regulatory bodies that failed to even understand what they were overseeing, let alone intervene. Perceptions of risk appear to be misaligned between the top and the bottom of organizations and there is a clear need to develop a common understanding of the risks, supported by tools where necessary, between executive management and those performing the actual operations. A well-motivated theoretical framework has been developed to allow the move from hindsight to foresight in the broad area of risk.

The project examines risk in the context of the need to become an advanced safety culture (a problem certain to be highlighted in official reports after Texas City was followed by Deepwater Horizon, both of those disasters appear to be primarily cultural problems within BP). Issues that are addressed include the personal perception of risk at different levels and functions, the ability and effectiveness of company learning in both single (what) and double-loop (why) modes. The results can also be used to design and validate company internal regulatory regimes and provide better levels of assurance to stakeholders – how can you run a high-risk enterprise from the centre of a major and highly distributed multi-national organization?

As was stated above, there is a growing disparity between the complexity of the risk problem and the desire and necessity to make things simple. Daily decision making needs to be quick and cannot be hampered by complicate analysis, although there is a need to make predictable where these decisions lead. Even although it is merely impossible to know where every water drop in a river goes to, it can be predicted how much water ends up at the mounding.

The challenge is to gain understanding what constitutes the flow of decisions, how they are shaped by internal and external forces and how this leads to the final result: sufficient safety, sufficient resilience or ruin.

3. Model structure

In more conventional approaches (e.g. Roelen et al, 2008), a mixed logic model is employed. In Ale et al (2009a) we described how the construction of one integrated BBN 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. For this development the mathematics of the BBN's were further developed, allowing continuous distributions (Kurowicka & Cooke, 2004)

In the current model the same approach is used to integrate all modelling into a single BBN. This includes the incentive structure which combines influences within the company and influences from personality and social context into a personal tendency to take a risk or to avoid it in a particular circumstance for a particular person, be it an operator, a manager or a decision maker.

3.1. Tripod

Tripod (Groeneweg, 1998) specifies the nature of the various barriers to protect against accidents in three kinds, faults, latent failures and preconditions. This way of distinguishing between different types of barriers is meant to take away usual way of designating the cause of the accident as the last fault or mistake made, which usually also puts the blame on the operator. Groeneweg (1998) tries to emphasise what Reason (1990) also argues, which is that the operator many times is put in a situation in which the accident has become unavoidable. This is illustrated in figure 1. In fact this is a situation that arises in many more cases that often is assumed. A system is designed and design decisions have been made, which lead to a situation that entices or even forces the operator to perform an action in another way than the designers had meant or had anticipated. Although in hindsight this is often called wrong, the action seemed completely normal for the operator. When this happens, the designers usually have long been gone, so nobody notices. Until the situation changes and some other condition occurs, which is abnormal. This then combines with the deviant action to create an accident. In the current development these gradual and often ignored changes are modelled and by way of the incentive structure it is estimated what the likelihood is that such changes occur and how this likelihood can be influences.

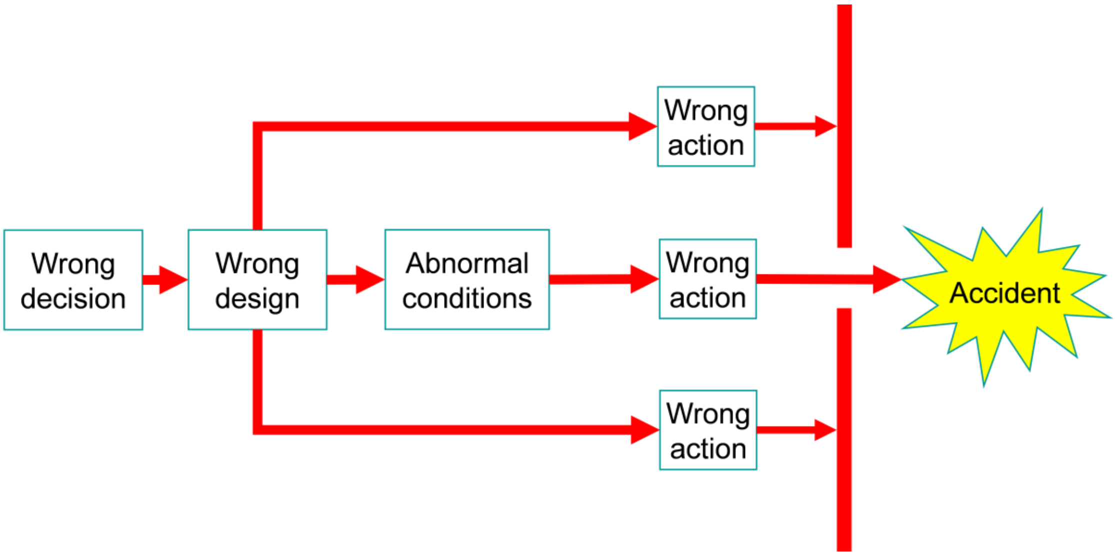

Figure 1. Preconditions and latent failures.

A similar situation exists for managers in a multilayer company. Decision making structures are set, directives are given, goals are defined. This, together with the psychology of the manager, drives for a large part the decisions he makes. It should be noted that this is in fact what the whole command and control function in a company is supposed to do: predefine the general direction of decisions that are taken when and where more, situation specific information is available. Just as top management aims at having the right decisions made, they are also responsible for the wrong decisions. Analysis of the structure of the decision making environment in incidents and accidents is or should be part of the investigative procedure.

3.2 Management model

The management model used in this project builds on the work done in I-RISK, WORM and CATS [Ale et al 1998, Bellamy et al, 1999; Ale; 2006, Ale et al, 2006; Papazoglou & Ale, 2007]. The model describes the influence of management on having safety functions in a "correct" state by distinguishing four tasks: to provide, use, maintain and monitor the risk control measures that need to operate to keep the system safe.
These safety functions serve to keep the system operating within its safe operating envelope for the whole of its life cycle. These tasks are as follows:

- Provide = specify, design and procure technology or human tasks and procedures
- Use = function (technology) or carry out defined actions (human)
- Maintain = restore function to designed level
- Monitor = check functioning of technology or people (inspect/observe)

For these tasks eight deliveries or "components of working safely" were distinguished in I-Risk. They are called deliveries because they are risk controls, instructions and resources that management should deliver to the tasks. The components are designed to be mutually exclusive and complete. That means that all of them need to be present to have the tasks correctly fulfilled and that no additional components are needed.

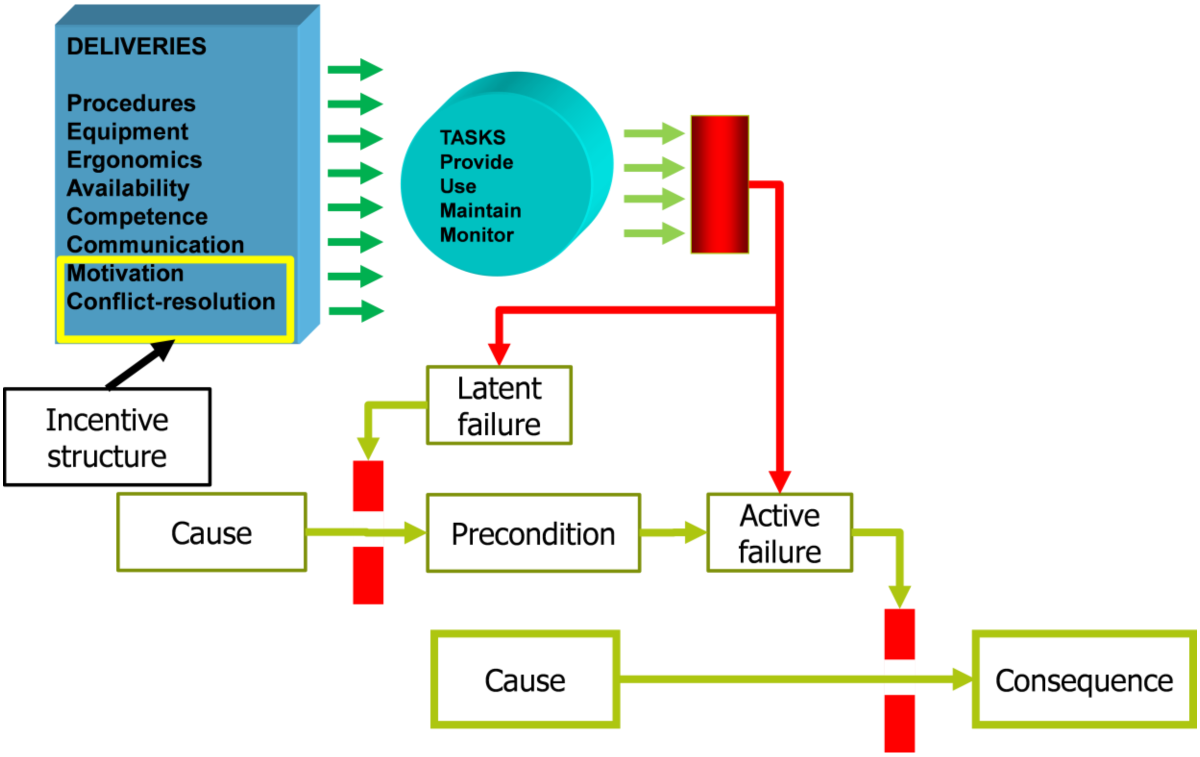

Figure 2. Deliveries and tasks of the management system

The method to implement the management influences in the BBN is through the change in the probability distribution of event modes in the BBN. This method was originally developed in IRISK (Ale et al, 1998) for single point estimators of probability and further developed in the CATS project to apply to probability distributions (Lin et al, 2008).

As can be seen in Figure 2, the combination of the management model with the TRIPOD event structure already introduces common cause influences, as can be expected with managerial tasks and interventions. This is another reason to construct the model as an integrated BBN (Hanea et al, 2012a) rather than using the more conventional mixed logic approach (Roelen et al, 2008).

In this model the IRISK management model is taken one step further, recognizing that some of the deliveries are only partly under management control. At this stage of development the influences of management on the deliveries “motivation” and “conflict resolution” were enhanced with influences from the social environment of personnel, such as managers, supervisors or operators (Lin et al, 2012)

3.3 THE BBN

A Bayesian Belief Network (BBN) represents a concise way of representation of joint probability distribution of a set of variables (Hanea et al, 2012b). By definition, a BBN is a directed acyclic graph in which nodes represent random variables and arcs represent probabilistic or functional influences (e.g.Pearl, 1988; Jensen, 1996, 2001). The introduction of the distribution free BBNs (Kurowicka & Cooke, 2004) allows the variables to be either discrete of continuous, and the influences to be represented by rank correlations or functional relations. The rank correlation between two probabilistic nodes represent the degree of association of high values of one variable with high (for positively correlated) or low (for negatively correlated) values of the other variable. On the other hand, functional nodes can be any analytical function having as arguments its parent (or influencing) nodes. This implies that also the logical deterministic relations between evens expressed in terms of Fault Trees can be transformed into BBNs. The transformation is possible by assuming that the Boolean variables (failure/not failure) from the base of a Fault Tree can be replaced by their probability of failure (or their expectations) and, then, the probabilities of the top events can be computed using ordinary arithmetic. This is true under the assumption that in the Fault Tree, each event appears only one time (Ale et al., 2009b, 2011,). The whole of the BBN described later in this paper has approximately 365 nodes and 430 arcs (see figure 3).

4. End Points

Since the company, as many others, monitors their day to day performance by way of indicators, the model outcomes are also converted into the – future expected – value of these indicators. The Key Performance Indicators used here are the following;

Accident free month:	The number of month passed since the last accident happened
Total reportable case frequency:	The number of times per year that a reportable case has occurred. These include accidents involving injuries and death, but also events that might have resulted in injuries, process upsets and a number of other unwanted events that are considered precursors of more serious incidents.
API process incidents:	A Process Safety Incident (PSI) according to the API guide is reportable if a Loss of Primary Containment (LOPC) occurs on company-wholly owned or operated refineries and petrochemical plants and results in one or more of the following: a. A fatality or days away from work incident; or b. A fire or explosion; or c. An acute release of flammable or combustible liquid, gas or vapour; or d. An acute release of a toxic chemical.
LOPC > 100kg:	This is a subset of the API process incidents. The limit of 100 kg probably stems from historical considerations, when it was believed that vapour clouds consisting of hydrocarbon-air mixtures with a combustible content of less than 100 kg could not give rise to an unconfined vapour cloud explosion (UVCE).

From these descriptions it can be seen that these KPI’s for a large part cover the same subjects and therefore are not independent indicators for the various risks the company is exposed to. As will be seen later it has not been determined yet in how far the results of the plant items under consideration in this proof of concept study cover these KPIs and how they should be scaled to be considered representative of the companies site as a whole. Additional measures of success were constructed in the form of the probability of a target value to be reached. As an example consider the target of having 9 consecutive accident free months. Given the probability of an accident it can be calculated what the probability is of reaching that goal. This probability conversely also is an indication whether reaching the goal is a meaningful result. If the probability of reaching the goal is high and the goal is reached, it could be considered as an expression of successful safety policy. If the probability is low and the goal is reached anyway, that might say nothing about the quality of the safety policy, as this may be purely by chance and will not occur again. With the current values of the probability of having a reportable accident of 1.6 per million hours the probability of having 9 consecutive accident free months is 0.06. The probability of reaching the value realised in 2010 of 2 month is 0.53, the even odds value is 2.1 month.

In any case the current realisation of the KPI's should be related to current estimates of probability. For this proof of concept it is assumed that that is indeed the case and the combined probabilities of the items in the current portfolio (overfill, run-away, pipe-break, occupational accidents) are in various combinations scaled to get to the current KPI values. This forms the starting point for the analysis of changing existing practices on the future value of these KPI's; or better: the future probability distribution of these values.

5. CONCLUSION

This paper described the proof of concept project for an integrated model for the risks of hydrocarbon industry operation. It feasibility of basing this model on previous work in the WORM project and the TRIPOD analyses for the installation and using the BBN approach developed in CATS is shown.

The initial analyses show that such common cause failures can be adequately modelled in the BBN system, without the need for artificial non-model correction factors. This does not take away the considerable uncertainties in the numerical evaluation that still exist and need further analyses, especially for the cases in which large investments are under consideration at the one hand, and large negative outcomes could be the unfortunate result on the other. Even though these numerical uncertainties exist, the comparison between different policies can be made on a much sounder basis, recognizing the overarching effect of human behaviour, on which the management of the company has a large, but not necessarily determining influence. Although the modelling and mathematics involved are much more complicated than in the past, the results can still be expressed in a way that is useful for management and their decisions. It also improves the understanding of time delays in the results of safety programs and the spending of money in safety, as well as the delay in time but nevertheless unavoidability of the consequences of not paying attention to safety.

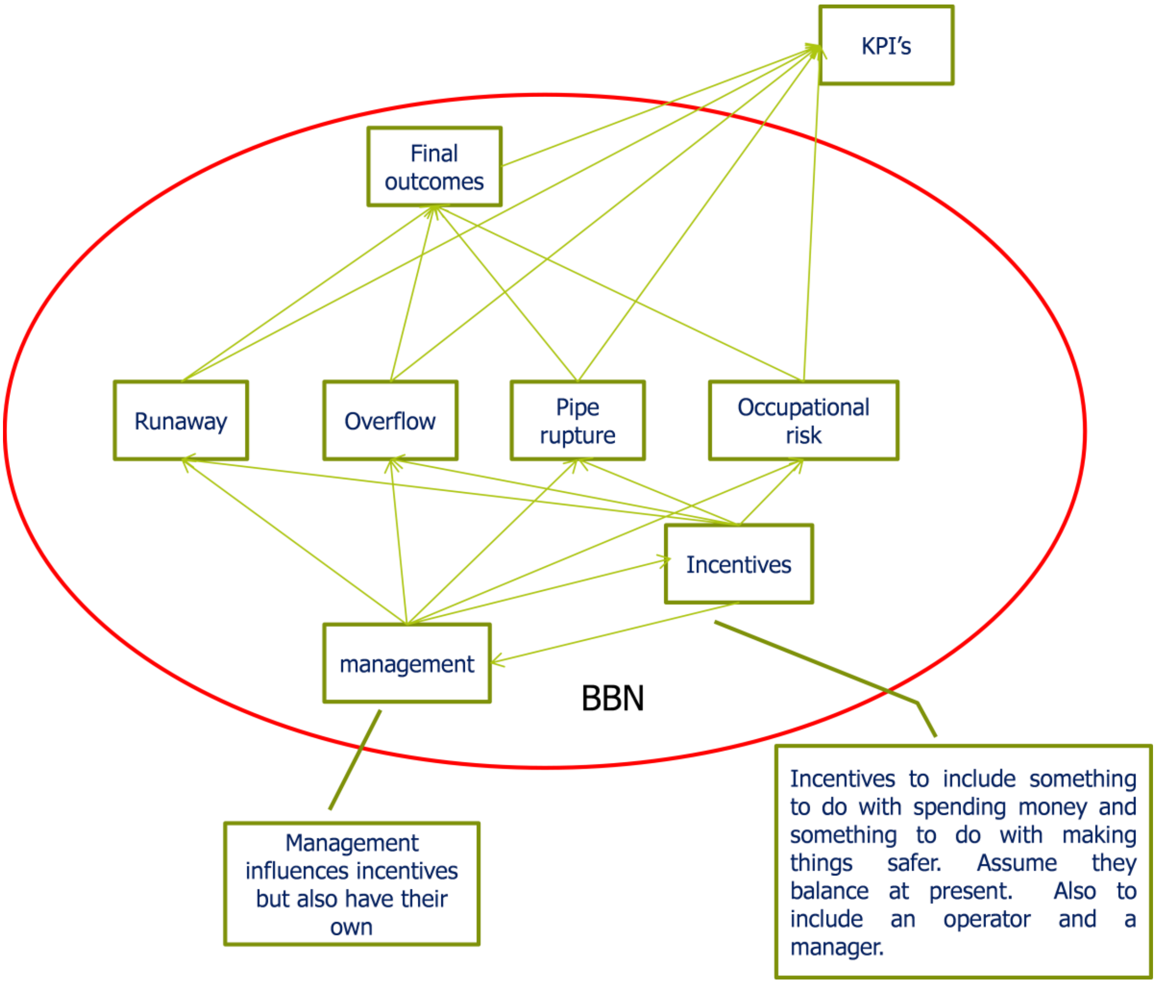

Figure 3, overall structure of the model

Although the results are still experimental and the model results should not be used as the only driver for a decision, the fact that the results of these models could be conveyed in meaningful language to managers of the company enticed the company to explore the potential of this approach even further in an effort to identify strategies that go beyond the current thinking about safety, about indicators and about rational risk management

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