RISK MODELLING OF A HYDROGEN REFUELLING STATION USING A BAYESIAN NETWORK

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ABSTRACT

Fault trees and event trees have for decades been the most commonly applied modelling tools in both risk analysis in general and the risk analysis of hydrogen applications including infrastructure in particular. It is sometimes found challenging to make traditional Quantitative Risk Analyses sufficiently transparent and it is frequently challenging for outsiders to verify the probabilistic modelling.

Bayesian Networks (BN) are a graphical representation of uncertain quantities and decisions that explicitly reveal the probabilistic dependence between the variables and the related information flow. It has been suggested that BN represent a modelling tool that is superior to both fault trees and event trees with respect to the structuring and modelling of large complex systems. This paper gives an introduction to BN and utilises a case study as a basis for discussing and demonstrating the suitability of BN for modelling the risks associated with the introduction of hydrogen as an energy carrier.

In this study we explore the benefits of modelling a hydrogen refuelling station using BN. The study takes its point of departure in input from a traditional detailed Quantitative Risk Analysis conducted by DNV during the HyApproval project. We compare and discuss the two analyses with respect to their advantages and disadvantages. We especially focus on a comparison of transparency and the results that may be extracted from the two alternative procedures.

1.0 INTRODUCTION

This paper gives a short introduction to Bayesian Networks[1] (BN) and utilises a case study as a basis for discussing and demonstrating the suitability of BN for modelling the risks associated with the introduction of hydrogen as an energy carrier.

The first phase of a risk analysis will typically be a *coarse risk analysis* which is conducted in order to better understand the problem. The coarse risk analysis represents a *risk screening*. A subsequent phase may extend the coarse risk analysis to a detailed risk analysis that focuses much more on

[1] Bayesian Networks are also known as Bayesian Belief Networks, Causal Probabilistic Networks, Causal Nets, Graphical Probability Networks, Probabilistic Cause-Effect Models, and Probabilistic Influence Diagrams

modelling the system interaction. System interaction is only to a limited extent included in the coarse risk analysis. In a detailed risk analysis, it is possible to take into account system effects and to combine various risks. Different tools are available for conducting a detailed risk analysis, e.g. Bayesian networks may be used to model the entire system within a probabilistic model universe.

When performing a coarse risk analysis it can be useful to calculate the yearly risk $r(A)$ associated with the event A as:

$$r(A) = \lambda \cdot P[barrier] \cdot c$$

In which λ represents the frequency of occurrence of the initiating event; $P[barrier]$ defines the probability of failure of the set of safety barriers that have been implemented to prevent the occurrence of the unwanted consequences, c. For instance, the unwanted event may be a hose rupture that might lead to a gas leak and subsequently to both material and human losses. A series of barriers are present, all of which must fail to let the leak become a "large" fire and for the consequences to materialize. For example a pressure sensor may be present, which must fail in sensing the pressure drop or in activating the shutdown to limit the leak; the leak must be ignited, and the staff must fail to detect the leak and fire in time. The probability of failure is estimated for each of these barriers. If it is assumed that all these individual barriers are independent, then the joint failure probability of the barriers, $P[barrier]$, becomes equal to the product of the individual barriers. Note that it is not always possible to assume that the barriers are independent. In these situations it is necessary to carefully take the correlation of failure into account. This approach is known as the barrier model or "Swiss Cheese model", Reason (1997).

To perform a structured risk analysis, it is important to define the set of consequences that should be included and to group, compare and balance these with each other. For instance, consequences may be grouped into categories involving loss types such as human life, assets, the environment and monetary losses. These categories are subdivided into coarse classes (negligible, minor, etc.) to reflect the severity of the events. The balancing implies that different loss categories belonging to the same class are comparable and hence equally critical. Although this fact may seem very simple, it is frequently forgotten in risk analysis. The loss assessment may involve tangible (e.g. direct economic losses, lost production, indemnification due to pollution) and intangible losses (e.g. loss of reputation, harm to nature and quality of life).

The objective of the risk analysis is to estimate the total expected loss resulting from the activity and to identify those elements or areas in the system that contribute the most to the total loss. When these loss critical elements are identified, it should be considered how the risk contribution from these may be reduced. The identified risk control measures may either have an effect on reducing the frequency of occurrence (either directly or through the barriers) or reduce the consequences – in some cases both are reduced. One objective of the risk analysis is to support the owner's decision-making by establishing the most efficient risk-reducing initiatives. The balancing of the consequences is therefore very important.

The options for reducing the consequences following the occurrence of an unwanted event will typically affect the emergency response plan or imply the introduction of passive devices that may absorb the energy resulting from the unwanted event. There may be consequences that seem so unacceptable that it is paramount to ensure a very low likelihood of their occurrence.

The coarse risk analysis may have problems in properly handling the correlation among the different variables in the system and/or it may be limited in its modelling of the consequence spectrum that might follow the occurrence of the unwanted event. Compared to fault and event trees (which frequently use only binary state variables – success/failure), BN are not limited to binary states[2] and have much more flexibility in modelling the interdependencies among the variables, and thus arrive at more realistic and useful results. The present paper will illustrate this.

2.0 DESCRIPTION OF THE CASE STUDY

This case study takes its point of departure in a selected input based on a detailed Quantitative Risk Analysis (QRA) conducted by DNV during the HyApproval project. This was a QRA of a hydrogen refuelling station (HRS) with on-site hydrogen production [1, 2], composed of "typical", "representative" units. Therefore, this case study is not based on a real HRS. In HyApproval [3], the virtual HRS was used to demonstrate relevant HRS safety challenges.

The purpose of this paper is to explore the potential benefits of using BN compared to traditional QRA, and to discuss and demonstrate the suitability of BN for modelling the risks associated with the introduction of hydrogen as an energy carrier. It was therefore decided to select one part of the HyApproval HRS as a basis for the comparison. As the dispenser area and the associated interaction between the vehicle and the user are often of special concern [4], it was decided to base the case study on the input for the gas dispensers. The case study HRS operates more vehicles, ie has more traffic, than most HRSs in operation today

The dispenser for compressed gaseous hydrogen (CGH_2) has facilities for filling vehicles with CGH_2 at 700 bar. Upon successful leak detection and shutdown, the dispenser will be isolated from the high pressure storage upstream.

3.0 METHODOLOGY

This paper utilises, discusses and compares two different approaches to risk assessment. The traditional approach is Quantitative Risk Analysis (QRA). This is compared with BN. The methodological approaches are described in the following.

3.1 Quantitative Risk Analysis

QRA is a systematic approach and methodology for the identification and quantification of a facility's risk contributors. A QRA can provide authorities and stakeholders with a sound basis for creating awareness about existing and potential hazards and risks [5]. Based on the findings from the QRA, potential measures to control and/or reduce the risk can be suggested, and the effect of the measures evaluated.

The QRA methodology applied is schematically illustrated in Fig.1.

Compile and Assess Data

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[2] Event trees are not limited to a binary state space, but an extension to higher dimensions quickly makes the tree so huge that it becomes almost impossible to validate it.

Available data [1] was examined and used to define the case study.

Hazard Identification

The Hazard Identification undertaken for [1] was used to define the scenarios. The main hazards from the QRA that are relevant to the dispensers and user interface are scenarios related to hydrogen gas leaks in the dispenser area.

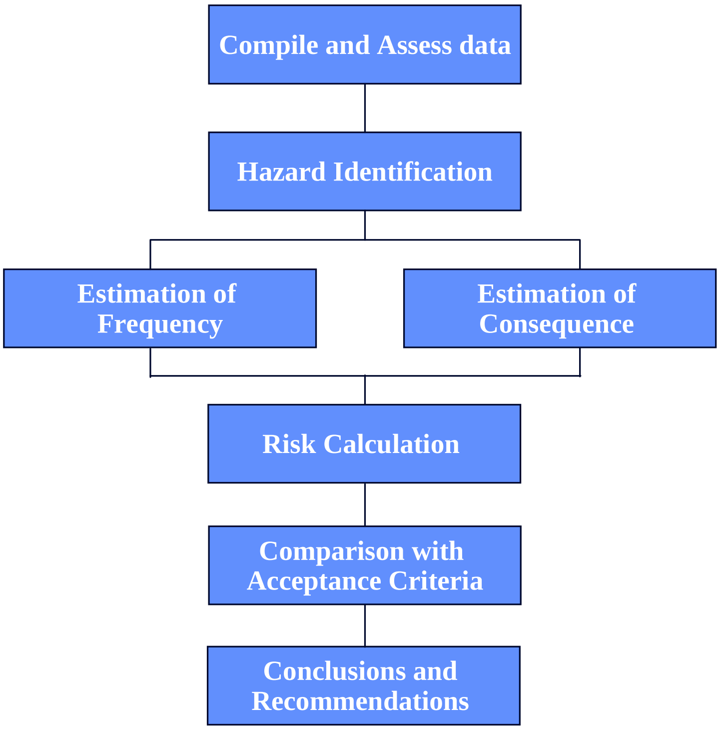

Figure 1. Illustration of the QRA process

Frequency Calculations

The frequencies of occurrence for the different hazards were calculated based on the available statistical data. When hydrogen-specific data was not available, data for “comparable” hydrocarbon events was used but adjusted to reflect the differences between hydrogen and hydrocarbons.

Consequence Calculations

Hazard-specific consequence calculations were carried out. In general, these calculations consider the case-specific release potential, and include assessments of gas build-up and dispersion as well as of the dimensions and duration of possible fire scenarios. Fires and explosions may affect people in a variety of ways, primarily related to heat and radiation and explosion overpressures.

Risk Calculations - Use of Event Trees

The QRA used Event Tree Analysis to assess the possible development of undesired events. The event tree provides systematic coverage of the sequence of event propagation. In event tree analysis, each event following the initiating event is conditional on the occurrence of its precursor event. In this QRA, the outcome of each precursor event was binary (Success or Failure; Yes or No).

The event tree used to assess the risk associated with the dispensers is shown in Fig.2. For this event tree, immediate ignition was defined as ignition caused by sparks or energy exerted at the time of the initial rupture/leak. Delayed ignition can occur if the release is not immediately ignited, and might cause the formation of a flammable gas cloud that, depending on the situation, might expose more and/or other ignition sources than those for immediate ignition. The consequences of the fire might also be different from a scenario with immediate ignition. Shutdown failure was interpreted as a failure to detect gas and failure to close the isolation valves on demand. Detection and shutdown could be initiated automatically and/or manually.

The end events were then assessed with respect to the potential impact on HRS personnel (first party), HRS customers (second party) and people that are not involved with the HRS (third party). In the QRA, this impact is estimated as the probability of lethal exposure. The reference study did not include assessments of the consequences related to the environment or material damage.

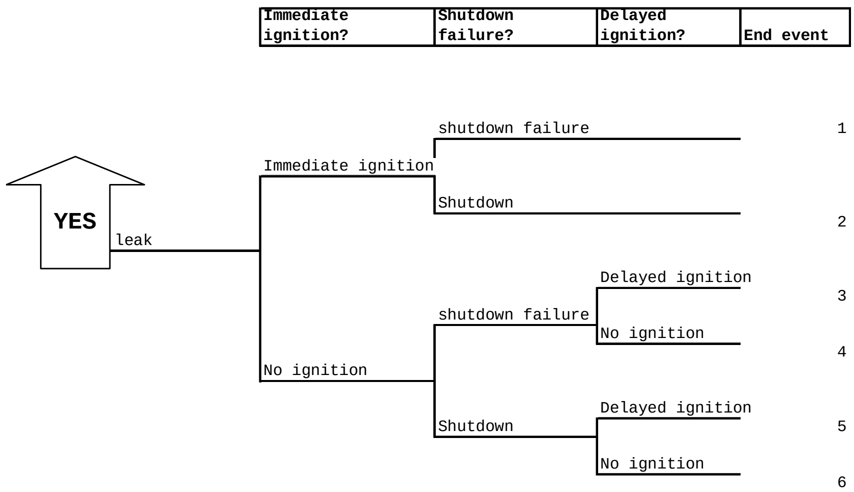

Figure 2. Illustration of the event tree used for the dispensers in the QRA

In its quantitative frame, the typical coarse QRA will only consider the quantification of the frequency of occurrence of the unwanted events. The ensuing unwanted consequences are normally only assessed according to coarse classes of increasing severity. In the typical QRA, the consequences are rarely quantified on a monetary scale. In this study we extend the preliminary analysis to estimate the loss caused by the consequences.

The *coarse risk analysis* represents a *risk screening* and is conducted to obtain a better understanding of the problem. The coarse risk analysis implies an assessment of the frequencies and the consequences. This analysis operates with a frequency matrix, a consequence matrix and a risk matrix, all of which are used in the quantification of the involved risks. An important simplification in the coarse risk analysis is that the analysis will normally have a focus on evaluating all the single components (or small systems) individually. System effects will normally only to a limited extent be taken into account in the analysis. It is very important to always remember this limitation in the analysis, as the omission may in some cases be the cause of gross errors in the risk assessment.

Frequency class	**Return period**	**More than X events per year**
2	Daily-Monthly	10
1	Monthly-yearly	1
0	1-10 years	0.1
-1	10-100 years	0.01
-2	100-1 000 years	0.001
-3	1 000-10 000 years	0.0001
-4	10 000-100 000 years	0.00001
-5	> 100 000 years	0.000001

Figure 3. Frequency matrix

In the frequency matrix, the frequency of occurrence of an unwanted event is divided into classes from one event per more than 100 000 years to as frequent as one event daily or monthly. The related frequency classes, Fc, are labelled from -5 to 2, see, Fig. 3. Note that the mean frequency of occurrence in each class is given by $\lambda_{\text{mean}} = 10^{Fc-0.5}$.

Similarly, the consequence matrix divides the consequences following an unwanted event into classes ranging from “None” through “Significant” to “Catastrophic”. These classes are labelled from 3 to 8. The consequences are further divided into whom or what the consequences affect, e.g. “First and second party”, “Production”, “Environment”, or a “Monetary value” (here €), see Fig. 4.

It is noted that consequences categorized as, for instance, “Significant” have the same weight in the risk analysis irrespective of what group they belong to. If the decision maker does not agree to the identical trade off between the different consequences, then it is necessary to adjust the definitions of what is “Significant” such that this trade off holds and that “Significant” has the same interpretation irrespective of the consequence referred to. The second last row in the matrix defines a corresponding monetary loss for each group. For the “Significant” class, the equivalent monetary loss is from €100,000 to €1 million. The defined correspondence is used in the conversion of all losses to a monetary scale in €. Note that the average monetary loss for each consequence class may be estimated by the class label, Cl, as $L = 10^{Cl+0.5}$.

label		None	Negligible	Significant	Serious	Critical	Very Critical	Catastrophic
Consequence Class	Abbreviation	2	3	4	5	6	7	8
First and second party	**PD**	Bruises and minor injuries that do not require hospital treatment	1 injury requiring hospital treatment	Several incidents requiring hospital treatment	Several incidents requiring hospital treatment. 1 disabled	1-10 killed	More than 10 killed	
Third party	**ND**	Uncomfortable, insecurity	Bruises and minor injuries that do not require hospital treatment	1 injury requiring hospital treatment	Several incidents requiring hospital treatment	Several incidents requiring hospital treatment. 1 disabled	1-10 killed	More than 10 killed
Production	**PR**		2 hour production stop	1 day production stop	1 week production stop	1 month production stop	1 year production stop	several years production stop
Material	**MK**		Minor repairs that can be done immediately by own crew	Repairs that take several days to carry out	Damage that takes weeks to repair and will affect the system	Damage that takes months to repair and cause serious consequences	Very large material damage	Significant parts of the system destroyed
Environment	**EM**		None/negligible	Minor environmental damage. Restored within days	Serious environmental damage. Restored within weeks	Serious environmental damage. Restored within months	Critical environmental damage. Takes 1-2 years to restore	Catastrophic environmental damage. Takes several years to restore
Monetary value (€)		**100**	**1 000**	**10 000**	**100 000**	**1 000 000**	**10 000 000**	**100 000 000**
Acceptability per year		Negligible	Tolerable	Unwanted	Unacceptable	Unacceptable	Unacceptable	Unacceptable

Figure 4. Consequence matrix

The last row in the consequence matrix defines the preferences regarding the different magnitudes of losses. This attitude depends on the size of the considered business and of the revenue generated by the business. In the example, the unacceptable limit is set at annual losses in excess of €100,000 per year. The tolerable limit is losses below €10,000 per year, whereas annual losses of less than €1,000 are considered to be negligible.

For each of the considered unwanted events, the frequency of the initiating event is first identified through its class, see Fig. 3, then the resulting consequences are identified by their consequence class, see Fig. 4, and finally any potential barriers for avoiding the unwanted event are identified and assessed. With this information, the risk of each event may be estimated as

$$r(A) = 10^{Fc-0.5} \cdot P[\text{barrier}] \cdot 10^{Cl+0.5} = 10^{Fc+Cl} \cdot P[\text{barrier}].$$

It is seen that the $P[\text{barrier}]$ acts as a thinning probability on the coarse risk estimate[3]. The calculated risk becomes directly represented by the expected annual monetary loss. The advantage of this is that it becomes much easier to compare and evaluate the different risks. Also, personnel with system knowledge will be much more qualified to validate the risk analysis. At least identified risks leading to disproportionate estimated monetary losses may be easily identified and further evaluated.

From the risk analysis, it is straightforward to aggregate and identify the total risk (expected annual monetary loss) and to evaluate whether such annual losses are acceptable. Further, it is easy to identify those areas that contribute the most to the total risk and thus should be subjected to an

[3] If the frequency of occurrence of the event is known, then the barrier probability may be used to adjust the coarse mean frequency to its exact value.

assessment of possible ways of mitigating these risks, either by reducing the frequency or consequences or by increasing the number of barriers that have been implemented.

Hence, the thus performed risk screening may directly be used as the fundament for selecting different risk-reducing measures. Alternatively it may be decided that a more detailed analysis is necessary and the coarse risk analysis may thus be used in defining the boundaries for a detailed analysis.

Risk-reducing measures

The objective of both the coarse risk analysis and the detailed risk analysis is to assess the risk in different areas. This is achieved by focusing on the probability of a specific unwanted event occurring and on the resulting consequences following the event. If the estimated risk is unacceptable, it is necessary to identify risk-reducing measures that reduce either the frequency or the consequences of the occurrence of the unwanted event.

For each individually considered risk element, it must be decided whether or not the investment in the risk-reducing measures has the effect of reducing the risk to an acceptable level. Using the principle laid out here, this cost benefit analysis becomes particularly simple, since the cost of the measure may be directly compared to the reduction in risk. If a given risk-reducing measure results in a reduction of the risk from say €175,000/year to €145,000/year, then this measure would obviously be recommendable if the cost of it is less than €30,000/year. Otherwise the risk-reducing measure costs more than the benefit from it and thus does not need to be implemented - unless required by regulations.

The risk analysis hence becomes an iterative procedure that continues until control is gained over all the unacceptable risks.

3.2 Bayesian Network

Some of the steps in the risk assessment using the QRA approach are also required for the evaluations using the Bayesian network. In particular this applies to: Compile and Assess Data; Hazard Identification; Frequency Calculations; and Consequence Calculations. For the purpose of this paper, these are therefore not elaborated on further in relation to the Bayesian network.

A Bayesian network consists of *nodes* that are connected by *arrows*. Each node represents an uncertain variable that will be defined through a possible *set of states*. The “Weather” node shown in Fig. 5, for instance, may contain the states {Good weather, Storm, Rain, Heavy rain, Fog}. At any point in time, only one of these conditions may be present (the states are said to be mutually exclusive). The choice of states implicitly reflects the time frame of the problem that is modelled. In the present case, the model’s time frame should be shorter than the time scale of changes in the weather. We may argue that the weather time scale could be of the order of six hours. (If the duration of the analysed problem extends beyond this time window, then the model should be modified to account for this extension.) The frequency of occurrence of the individual states in the “Weather” node may be found from meteorological recordings. The arrow shows the *direction of the causal relationship* between the nodes. For instance, the “Weather” node will have a direct causal effect on “Visibility”. The states of the “Visibility” node may be defined as the visible distance in kilometres, such as {0-0.25 km, 0.25-0.5 km, …, 25-30 km}. The fact that the visibility is defined *conditional* on the weather makes it much easier for people with system knowledge (experts) to assess, judge and justify the probability distribution over the individual states. The estimated probability distributions are not shown.

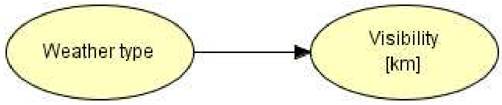

Figure 5. Simple Bayesian network that describes the causal relationship between the weather condition and the meteorological visibility

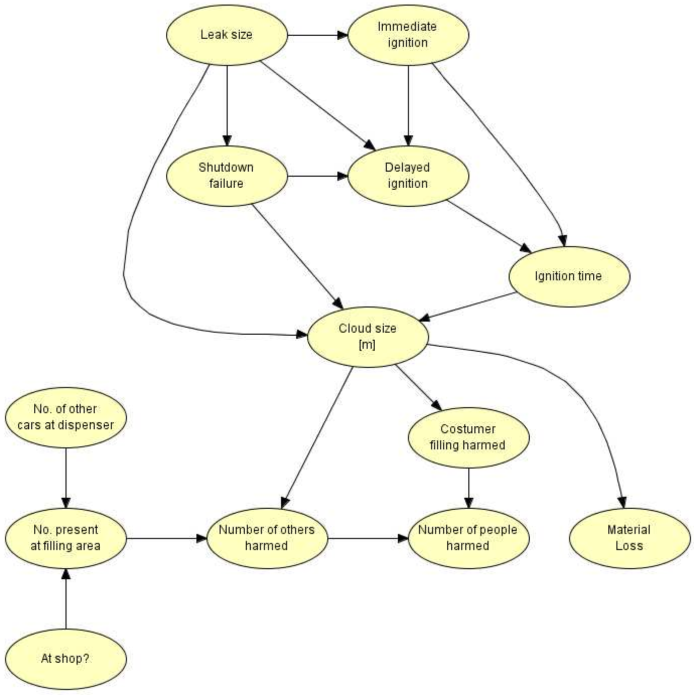

Figure 6. Bayesian network modelling of the dispenser area of the hydrogen refilling station. The top four nodes are equivalent to the original event tree

The probability distributions of the individual nodes will in general be evaluated on the basis of either statistical data, expert assessment or a or a combination of these two methods.

Since the network is built with a focus on the causal relationship, it becomes more straightforward for experts to evaluate whether or not the overall probabilistic model represents a useful approximation to reality. The model transparency is one of the important advantages of modelling complex systems using BN. People who possess system knowledge may quickly learn the modelling's intuitive principle such that they can confidently ensure that the model-realism is captured to an appropriate degree.

To illustrate the usefulness of Bayesian network modelling, we have made two constructs of the dispenser area of the hydrogen refilling station. The first is equivalent to the event tree analysis of the original study but extended to also include the consequences. This network is shown in Fig. 6. The network in Fig. 7 is a reconstructed model to better reflect the actual hydrogen refilling station. This network is still under construction.

The four upper nodes in Fig. 6, “Leak size”, “Immediate ignition”, “Shut down failure” and “Delayed ignition”, represent the event tree illustrated in Fig. 2. This part illustrates that “Immediate ignition” and “Shut down failure” are conditionally independent, whereas “Delayed ignition” is conditionally dependent on both of these. It would have been more transparent to merge the two nodes “Immediate ignition” and “Delayed ignition” into a single node “Ignition time” with the states ‘None’, ‘Immediate’, and ‘Delayed’. This node has been added, but was not part of the original event tree. Given “Leak size” and “Ignition time”, the “Cloud size” of the ignited fire can be estimated. The states of this node range from 0 m to 23 m to represent the dimensions of possible fires identified from the CFD analysis. On the basis of the “Cloud size”, the number of people harmed and the material loss are estimated. The results of this network are described in the subsequent section.

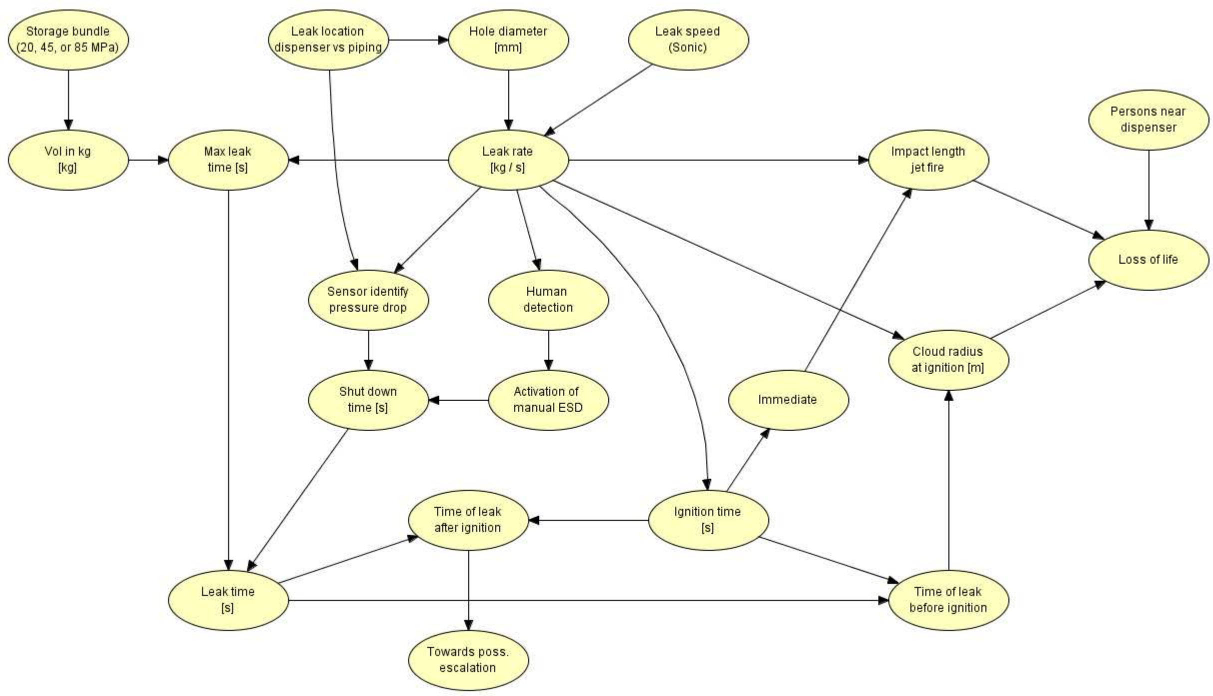

Figure 7. Extended Bayesian network modelling of the dispenser area of the hydrogen refuelling station

The network in Fig. 7 extends the simple event tree model to establish a more accurate model of the situation in the reference case study. This model is still under construction and we will not describe the causal modelling in detail. The network takes into account the storage bundle that will be active while a vehicle is filling hydrogen. It may further be noticed that the model shows the shutdown procedure in more detail. A perceived critical element in the shutdown procedure is the possible delay in the time it takes to identify a small leak and activate the manual emergency shutdown.

4.0 RESULTS

Based on the Hazard Identification in [1], the scenarios considered in the QRA were small and large leaks from the gas dispenser (compressed hydrogen gas). In the coarse risk analysis we considered the following scenarios from the gas dispenser scenarios (compressed hydrogen gas): jet fire due to small leak, flash fire due to small leak (delayed ignition), flash fire and jet fire due to small leak (shutdown failure, delayed ignition), jet fire due to large leak, flash fire due to large leak (delayed ignition), and flash fire and jet fire due to large leak (shutdown failure, delayed ignition).

The tables below show the estimated risk shown by the coarse risk analysis. The top table shows that the total annual risk (monetary loss) is of the order of €30 000. The bottom table shows how the losses are distributed among the different consequence categories. From the table, it can be seen that most of the losses stem from third party injuries and loss of life (here defined as the customers).

Hydrogen refilling station	Total Risk	Estimated loss
CGH2_Minor	3,2	1 534
CGH2_Major	4,5	31 139
Total	4,5	32 673

HyApproval	First and second party		Third party		Production		Material		Environment		Total Risk
	PD	Sum	ND	Sum	PR	Sum	MK	Sum	EM	Sum	
CGH2_Minor			219	*219*	626	*626*	626	*626*	63	*63*	1 534
CGH2_Major			30 047	*30 047*	399	*399*	631	*631*	63	*63*	31 139
Total			*30 266*	*30 266*	*1 025*	*1 025*	*1 257*	*1 257*	*126*	*126*	32 673

A rapid overview of the estimated losses may be obtained by plotting the risk results in a risk matrix. Fig. 8 shows the resulting risk matrix. All the events considered are represented by an id and plotted in the matrix.

HyApproval			Consequence						
			(2) None	(3) Negligible	(4) Significant	(5) Serious	(6) Critical	(7) Very Critical	(8) Catastrophic
			100 - 1 000	1 000 - 10 000	10 000 - 100 000	100 000 - 1 000 000	1 000 000 - 10 000 000	10 000 000 - 100 000 000	>100 000 000
Frequency (number per year)	(2) Daily - monthly	>10 per year							
	(1) Monthly-yearly	1 - 10 per year							
	(0) 1-10 year	0.1 - 1 per year							
	(-1) 10-100 year	0.01 - 0.1 per year			CGH2_Minor				
	(-2) 100-1000 year	0.001 - 0.01 per year		P1.4; P1.8; P1.12	P1.2; P1.3; P1.6; P1.7; P1.9; P1.10; P1.11				
	(-3) 1000-10 000 year	0.0001 - 0.001 per year		P2.4	P1.1; P1.5; P2.2; P2.3; P2.6; P2.8; P2.12	P2.7; P2.10; P2.11	P2.1	HyApproval; CGH2_Major; P2.5; P2.9	
	(-4) 10 000-100 000 year	0.00001 - 0.0001 per year							
	(-5) > 100 000 year	<0.00001 per year							

Figure 8. Risk matrix. All the events considered are represented by an identifier. From the location of the "HyApproval" it can be seen that the total risk is governed by "Very critical" consequences stemming from rare events (return period 1 000-10 000 years). The basic events are P2.5: Flash fire due to large leak and P.2.9: Flash and jet fire due to large leak.

The two most dominant single events are P2.5: Flash fire due to large leak (shutdown failure, delayed ignition), which represents a calculated annual loss of around €15 000, and P.2.9: Flash and jet fire due to large leak (delayed ignition), which produces an annual loss of around €12 000. Both these events were assessed by the Bayesian network methodology to have the potential to cause more than one fatality.

The coarse risk analysis is coarse, and in some cases it may therefore be necessary to establish a more detailed model to properly capture the model's interactions and details. We recommend using BN for this. We use the example construct presented in Fig. 6 to illustrate a few of the advantages of using BN. Firstly, because of the graphical representation, it is reasonably straightforward for third parties to capture the level of detail of the modelling and also how the analyst has interpreted the system's functional model. This understanding is very important as it facilitates validation by employees who have specific knowledge about the real system. Secondly, it is easy to play with the model by entering evidence and testing how the model reacts to such evidence. Thirdly, when evidence is entered it is also straightforward to identify the most likely configuration of the model that led to this event. This type of propagation is called a max-propagation. This information is highly relevant when searching for efficient areas in which to implement risk control options.

By performing a max propagation conditional on the number of fatalities, we find that the most likely condition for one fatality is a small fire, ignited immediately. For two or more fatalities, the most likely condition is similar to the previous one apart from the fire being large. The analysis indicates that the safety system is functioning well. In the extended network we will model the safety system in more detail in order to better understand the weaknesses of that system.

5.0 DISCUSSION

One main advantage of the Bayesian network applied here is that the results quantify the estimated monetary loss resulting from the different scenarios. This is of course also possible for standard QRAs and is normally done when the stakeholder requesting the analysis asks for it.

When quantifying risk, it is important to have access to relevant accident and incident information. The availability of hydrogen-specific incident and accident information is limited, making a direct estimate of incident frequencies challenging. When sufficient statistical data on historical hydrogen incidents was not available, data for hydrocarbon incidents was used. The use of hydrocarbon data to assess hydrogen risk represents a source of inaccuracy for risk assessments irrespective of whether the methodology applied is a Bayesian network or a traditional QRA. Both methods are equally dependent on good and reliable data input. It could be argued that the transparency which could be obtained by BN could make it easier to validate the use of such data, provided suitable experts are available for such validation.

5.1 Bayesian network versus QRA

In general, risk analysis problems constitute complex systems that require the modelling of interrelationships between different technical disciplines as well as humans and organizations.

While event trees are graphical representations of a logical model that identify and quantify possible outcomes following an initial event, a Bayesian network is a graphical representation of uncertain quantities and decisions that explicitly reveals the probabilistic dependence between the variables and the related information flow. Both approaches use a graphical representation to visualize the risk assessment methodology.

The nature of the BN allows greater freedom and flexibility to analyze and visualize the dependence between the different variables than a standard event tree. This can make validation easier for third parties as it might be easier to follow the logic behind an analysis. Much of the Bayesian analysis of the probabilistic dependence between variables will be integrated into the traditional QRA by the analyst. Therefore it may be more difficult to understand for someone unfamiliar with the specific analysis or methodology.

Although it is easier to visualize the logic of the analysis when BN are used, these networks may also become complex and difficult to follow unless they are designed very carefully. Both methods therefore require the careful design of the representation of the system to be studied for maximum transparency and to facilitate validation.

For both methods, it is also important to utilize good modelling tools. The underlying modelling in a Bayesian network may not be any easier to follow than the underlying modelling in a QRA. This partly depends on the specialists utilizing and developing tools to apply these methodologies. The further development of such tools and further development and refinement of the methodologies are recommended.

6.0 CONCLUSIONS

This paper has explored the potential benefits of using BN compared to traditional QRAs.

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