QRA INCLUDING UTILITY FOR DECISION SUPPORT OF H_2 INFRASTRUCTURE LICENSING

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ABSTRACT

Rational decision making in land use planning and licensing of H_2 infrastructure surrounded by other industrial activities and population should take account of individual and societal risks. QRA produces a risk matrix of potential consequences versus event probabilities that is shrouded in ambiguity and lacking transparency. NIMBY and conflict are lurking. To counter these issues, risk analysts should therefore also determine the utilities of decision alternatives, which describe desirability of benefits on a single scale. Rationally weighing risks versus benefits results in more transparent and defendable decisions. Example risk analyses of two types of refueling stations and three hydrogen supply transportation types applying Influence Diagram/BBNs are worked out.

Keywords: risk assessment, influence diagram, decision making, land use planning

1. INTRODUCTION

New technology involving hazardous materials comes with certain risks, especially when it is introduced on a large scale and becomes widely distributed to involve many people, not only in planning stages, design, and construction, but even more in operation and use. In such circumstances, just as a consequence of large numbers, incidents and accidents will be unavoidable despite inherent safety measures built into the system. One accident with fatalities and spectacular effects dramatized in the media will stir up public concern and generate ‘viscosity’ in land use planning and licensing processes.

Hydrogen is a very clean and useful replacement of common fuels such as gasoline and can be applied as a fuel in (micro-) Combined Heat and Power (CHP) systems for dwellings and offices. Its use could therefore become widespread, certainly as a means to counter the climate change problem. In most applications, it will have to be stored in a compressed gaseous state, and due to its size as a molecule, it will be leak prone. Alternatives are liquefied (boiling temperature 20 K) and absorbed, e.g., as a hydride. When mixed with air, its properties are known from a hazard point of view: high reactivity, low ignition energy, and wide explosive limits. Explosions in the open and fire cannot be excluded. Both the USA EPA RMP rule and the EU Commission Seveso Directives have set a storage quantity of 5000 kg (US 10000 lbs) as a threshold for invoking special major hazards regulation for land use planning and licensing an activity. The regulation translates to safety distances and other measures. Refueling stations and replenishment means, such as tank trucks and pipelines, will require licensing. When changes in the neighborhood are imminent, despite the importance of the overall goal, the public often takes an attitude of NIMBY (Not In My BackYard) when the reputation of the material involved is not pristine.

In Europe, due to the high density of industry and population, hazardous material accident risks are judged not only by their potential effect and end-points but also by likelihood of mishap. Risk analysis is a means to enable assessment, which is the basis for decision making. To that end, quite a few software package tools are available. In case of conflict of interests, common criticism of the risk assessment tools voiced by a resisting party is lack of transparency, uncertainties in models and data, and lack of confidence limits. In the political arena, uncertainty is translated into emotion resulting in strong precaution, which in quite a few instances has severely delayed the introduction of new technology. Where improvement of sustainability is pressing, unnecessary delays should be avoided.

In recent years progress in development of probabilistic methods and algorithms based on the Bayesian approach, fostered by the artificial intelligence community to enable automated reasoning, is broadening and deepening the scientific basis for decision making. An objective of this paper is to investigate what these developments can contribute to faster and more open risk assessments.

2. BAYESIAN NETWORK AND INFLUENCE DIAGRAM METHODOLOGY

In technical processes with large amounts of hazardous materials, many variables influence scenarios in which a spill results in damaging effects on people, structures, and the environment. These variables include material and process variables, environmental factors such as weather, geography, population density, and also human decision and intervention in the process. A scenario is described in cause-consequence event chains. Because of the many possible scenarios, prediction of resulting events by relating the variables cannot in practice be deterministic but is stochastic in nature: each outcome has a probability of occurrence. In their simplest form, stochastic variables have only discrete values, but because of the many possibilities involved when analyzing possible scenarios of mishaps in large technical installations, one often has to resort to continuous probability functions to describe them.

The Bayesian statistical approach facilitates the usual case in which part of the needed information is *a priori* available in measured data and functional relations or as expert knowledge, and part is uncertain and unknown. The unknown part can be updated *a posteriori* and the uncertainty reduced by later experience applying the basic laws (product and sum rule) of probability theory. This approach enables inference of determining the effect on an outcome by later observations.

Cause-consequence chains represented in fault and event trees, bowties, or master logic diagrams are mathematically described as *acyclic directed graphs (digraphs)* and usually conceptualized in risk analysis as fault and event trees, but a more flexible approach is by means of Bayesian belief nets (BBN) of conditional probabilities. These nets describe a system or process of linking stochastic system parameter nodes through arcs. In its simplest form, the node contains the possibilities to be considered and their discrete probability values. The arc communicates the possibilities and represents the operation of computing the joint probability values of the variables in connecting nodes. The net is Bayesian in the sense that it describes a system as it generally behaves based on measured inputs and results derived from statistical observation. ‘Belief’ is included with variables that represent expert opinion. By observing (updating) an input variable value for a particular case, the net can make an adapted prediction of outcome probabilities. There are many different applications of such inference by means of BBNs. A medical application for example is diagnosis of a disease, which can have different causes and is accompanied by a variety of indications of which the occurrence probability is influenced by a specific cause. For this purpose, the net can be extended by a decision node and by cost nodes and is then called an influence diagram (ID). An ID structures the decision making process by spelling out the probabilities of obtaining resulting utility values. In the net also, sensitivity nodes can be linked to input parameters showing in the end the range of uncertainty on the resulting expected utility values.

There are several software packages available in which the algorithms are embodied. Here, the GeNIe 2.0 package developed by the Decision Systems Laboratory of the University of Pittsburgh [1] for the

MS Windows operating systems was used. This package offers as an alternative to apply a net of nodes and arcs that enable application of arithmetic operations on continuous probability and other functions including logical and conditional probability functions. Computing the convolution of distributions and solving equations is by discretization. Such a net is suited to describe a complex scenario of a hazardous material spill and the consequences in terms of victims and damages by effects of fire, explosion, or toxic spread given a population density and environmental conditions. The representation is transparent, because any interim result can be made easily visible. It is flexible in that adaptations can easily be made while the effects of preventive and protective measures can be included. Risk calculation results with this kind of net can then be used in an ID, since risk assessment is to support decision making. The discrete version of the net can be made dynamic by introducing a temporal plate enabling e.g., representation of degradation processes by time slice updates.

3. RISK ANALYSIS HYDROGEN DISTRIBUTION SYSTEM

From a land use planning perspective, a generic model without specific local details will give a first impression. Considered will be hydrogen refueling/tank stations with compressed gas (GH2TS) and liquefied hydrogen (LH2TS) stores as well as transportation from an interim storage or production plant at a city's periphery at 15 km distance to the stations by tank truck (GH2TT) with compressed gas or with liquefied H_2 (LH2TT), or by Φ 150 mm pressurized gas pipeline (GH2PL). The input data for these 5 items are collected in Table 1. Annual delivery to a station is assumed to be 4.10^5 kg. Individual and group risk levels are calculated for the case of a release event as well as direct materiel damage and overall losses expressed in monetary terms (not including damage on the longer term, such as business interruption). An example of an analysis net is shown in Figure 1.

Table 1. Input data to the five considered storage tanks

H2 store	Pressure bar	Store Capacity kg	Event Frequency /yr	Ref.	Note	Hole size distribution fitted to literature data
GH2TS	30-200	960	1.00E-02	2		Lognormal(μ = 0.085, σ = 0.9)
GH2TT	30-160	300	5.33E-03	3	a	1+10*Binomial(μ = 2, σ = 0.3)
GH2PL	24	270	5.40E-03	3,5	b	Bernoulli(0.33)= rupture/large leak = 0.33:0.67
LH2TS	8	800	1.00E-03	3		-200*Weibull(λ= -0.26, k = 0.62)
LH2TT	8	4000	2.50E-04	3	c	Bernoulli(0.3) = rupture/large leak = 0.3:0.7

Notes: a. Compressed gas trucks make 1333 hauls annually, driving 10 km urban freeway at 2.10^{-6} accidents/km and 5 km urban road at 6.10^{-6} /km with 5% chance of a leak per accident yielding $3.33.10^{-3}$ release event per year. To this is added 2.10^{-3} /yr rate of failure of the tubes in static condition included in GH2TS.

b. An event can result in rupture or large hole leak. The effect of pinhole leaks is neglected.

c. The truck makes 100 trips/yr at an assumed chance of 0.05 of a release in case of accident.

Load capacity inputs have been gathered from various sources, e.g. [3] and are meant to be generic. Important are failure rates and leak size distributions. For compressed gas, installation failure data were taken from LaChance et al. [2] (hydrocarbon leak data base adapted to hydrogen by applying Bayesian theorem), for liquefied hydrogen equipment failure rates from Rosyid [3] (fault tree based); for traffic accidents of tank trucks U.S. statistical data [4], and for gas pipeline European information [3, 5] is used. From the data, both an event frequency was extracted as well as probability data of leak sizes given an event. The latter data was fitted with a probability distribution function as shown for each case in Table 1. Results of the fit are in some case rough but justified in view of the relatively large uncertainty inherent to the data. (Also, distribution function free, so-called non-parametric BBNs have recently been developed [20] and shall be available for future use). The store content on any moment is modeled as a uniform distribution between a minimum and the maximum given in Table 1.

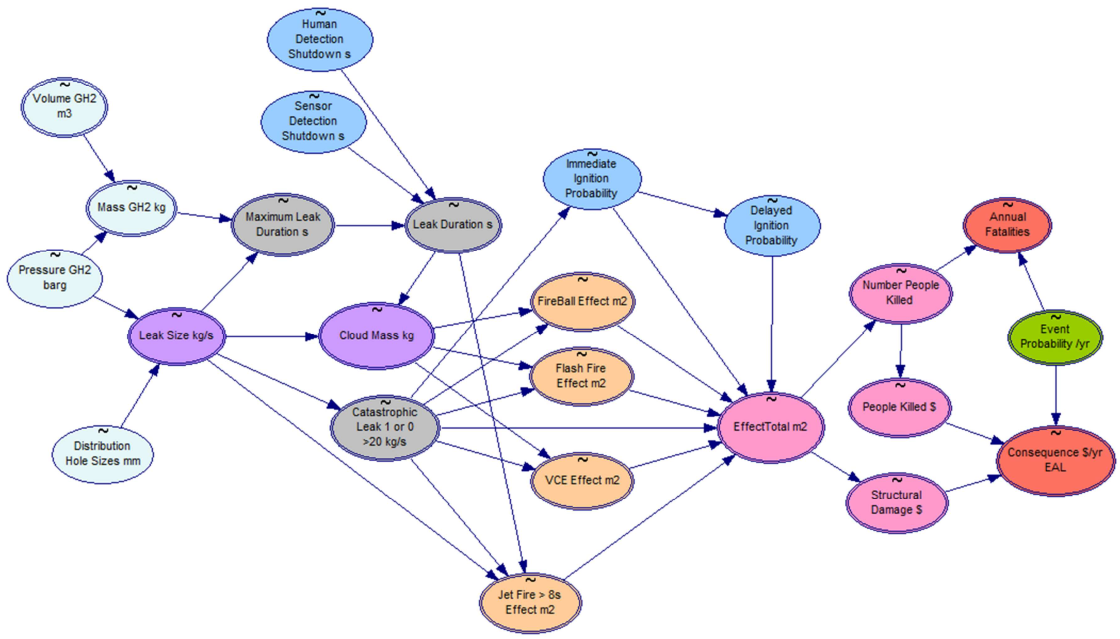

Figure 1. Example of a GeNIe [1] risk analysis net of a tank station storing hydrogen in compressed gas tanks. In the example automatic or human leak detection and shutdown is foreseen, but additional measures could be included. In case of LH2 and with immediate ignition, a pool fire can occur.

For the calculation of spill rates and effects of fire and explosion (jet fire, flash fire, fire ball, pool fire, and vapor cloud explosion - VCE), use was made mainly of Yellow Book models [6]. The release was qualified as catastrophic and assumed to be the result of rupture, if in case of compressed gas the spill rate was larger than 20 kg/s and in case of liquid 100 kg/s. The fire heat radiation intensity and the explosion blast overpressure effects were modeled for a certain standard mass of material and converted for each case in proportion to an adequate power, e.g., cube root of half the released total amount. The Surface Emissive Power, SEP value of the fire ball was assumed to be 150 kW/m^2, taking account of the data in [7]. For calculating the effect of VCE, half the mass at stoichiometric condition was taken as producing the combustion energy for the multi-energy model. The other half of the material was supposed not to participate in the reaction. Taking half the material reacting holds too for calculating the size of a flash fire of an evaporated quantity of LH2. The effect of jet fire of a compressed gas leak was supposed to be proportional to the size of the leak but independent of the total quantity released over time, because the flame will only cover a fixed area. However, the effect doubled if the jet lasted longer than 8 seconds due to the larger distance people would become lethally injured at that radiation duration. The jet flame from a pipeline leak was assumed to be vertically upward, so it irradiates only a limited space in the horizontal plane.

The effect of a burning jet of LH2 under a pressure of 8 bar, which will be a violently boiling two-phase flow, is not simple to estimate also, because no experimental data are available. Rosyid [3] applied the PHAST model and obtained an elliptic 56% lethality area with a half-length of 66 m and a maximum radius of 18 m for a 4000 kg load. For 240 and 40 m^3 LH2 spills, Verfondern and Dienhart [8] determined pool size, which appears to be scaled about linearly with spilled volume $V^{0.43}$. For a spill of 56 m^3 or 4000 kg, the pool radius will become 22 m. The area contour of 50% lethality (reached at an intensity of 37.5 kW/m^2), assuming a SEP value of 150 kW/m^2 and a view factor equaling the square of flame radius/distance to target ratio, will have twice the size of the pool and hence a radius of 44 m. This result would mean that burning in the end the same amount of fuel, a short lasting flame of a pool after a sudden rupture would have not even twice the 50% lethal area of a burning jet release from a large hole over a much longer time. It seems therefore justified to reduce the LH2 jet radius and the flame length effect values by 25%, while it is also scaled linearly with the leak rate. Below 8 seconds duration, the effect area was assumed to be similar to the effect area caused by half the leak size as before with the gas jet.

In this way, 50% lethality area distributions were calculated on the basis of the input leak size / cloud mass distributions. According to probit data this means at the perimeter of the area a heat radiation intensity of 37.5 kW/m^2 for 8 seconds [9] and an overpressure of 0.3 bar for people indoors [10] (a value which by the Dutch authorities is applied as the 100% lethality level [11] both in and outdoors). The shape of the area was assumed circular except in case of jet fire, where experimentally based data were obtained from LaChance et al. [2] and flash fire in which a run with the U.S. EPA ALOHA dispersion model [12] provided (approximately) the elliptic shape of the cloud. The explosion intensity was calculated with the Multi-energy method presented in [6] applying strength 7-10 (hydrogen is highly reactive while delayed ignition and built-up environment increase chance of accelerated flame; in the far field the exact strength is less important). The equations are summarized in Table 2.

Table 2. 50% Lethal effect area equations developed for various types of fires and vapor cloud explosion (SI units: area in m^2, mass in kg, leak size in kg/s).

Effect m^2	Case	Catastrophic leak	Leak
Jet fire	GH2TS/TT	0	π*15*LeakSize (+π*15*LeakSize, if leak duration >8 s)
	GH2PL	π*4*4	π*2*2
	LH2	0	π*18*0.75*66*0.75*(LeakSize/30.4)/2 (+π*18*0.75*66*0.75*(LeakSize/30.4)/2, if duration >8 s)
Flash fire	GH2TS/TT	π*60*4*(CloudMass/52)^0.333	π*45*3.7*(CloudMass/52)^0.333
	GH2PL	π*(100/2)*10/2	0
	LH2	π*18.6*121*(CloudMass/800)^0.333	π*15.4*88*(CloudMass/800)^0.333
Fire ball	GH2TS/TT	π*(25^2)*(CloudMass/300)^0.333	0
	GH2PL	0	0
	LH2	π*(25^2)*(CloudMass/300)^0.333	0
Pool fire	GH2	0	0
	LH2	π*((0.0158*((CloudMass/71)^0.43)^2+3.8121*(CloudMass/71)^0.43)*2)^2	
VCExpl.	GH2TS/TT	π*(25^2)*(CloudMass/20)^0.333	π*(25^2)*(CloudMass/40)^0.333
	GH2PL	π*(78^2)*(CloudMass*0.5/300)^0.333	0
	LH2	π*(62^2)*(CloudMass/300)^0.333	π*(62^2)*(CloudMass/600)^0.333

The calculated areas have to be multiplied by the corresponding ignition probability values and summed to obtain the probability weighted total area. Several authors developed event trees with estimations of ignition probability values. Only very little hard evidence based on hydrogen incidents is available. However, in case of hydrocarbon leaks over the years, considerable evidence has been collected [e.g., 13]. Hydrogen ignites in air at very low ignition energy while also the possibility is observed of ‘spontaneous’ ignition of hydrogen released suddenly at high pressure. It was therefore assumed that in case of a catastrophic leak of compressed gas in 80% of cases, immediate ignition would take place resulting in a fire ball or in case of large hole with 60% ignition chance producing a jet fire. The remaining 20 or 40%, respectively, will be equally divided over delayed ignition and dispersal without flame. Delayed ignition can result in a flash fire if the delay is moderate and in a vapor cloud explosion if the delay is longer or conditions for explosion are more favorable. Both possibilities were estimated to have equal chances. Because in case of the compressed hydrogen refueling station (GH2TS) as a result of the safety measure no release became catastrophic, in Table 3, which shows beside assumed also resulting figures, the latter probability values are both 0.1, and safe dispersal probability is 0.2. For a GH2 tank truck, the results have slightly shifted as catastrophic leaks resulting in fire balls can occur to some extent. In case of a pipeline rupture or large leak due to soil cover, only 50% chance of immediate ignition is assumed. This scenario will result in an upward directed jet flame. Because in case of a leak the gas will escape over a relatively long time and be more easily dispersed, no delayed cloud ignition is considered. Only rupture can result in delayed ignition, which again is equally divided over VCE and flash fire possibilities.

Liquefied hydrogen release will also be immediately or with a very short delay ignited with 80% chance. When rupture takes place, this will yield a fire ball in half the cases and a pool fire in the other half, or in case of a large leak a jet fire instead of a fire ball and a pool fire. If still no ignition has taken place in 40% of cases, delayed ignition is assumed to occur, resulting in either flash fire or VCE.

Table 3. Assumed and resulting ignition probabilities.

H2 store	Immediate ignition		Fireball	Flash fire	VCE	Jet fire	Pool fire	Safe dispersal
	Catastrophic	Hole						
GH2TS	0.8	0.6	0	0.10	0.10	0.60	0	0.20
GH2TT	0.8	0.6	0.05	0.10	0.10	0.55	0	0.21
GH2PL	0.5	0.5	0	0.08	0.08	0.50	0	0.34
LH2TS	0.8	0.8	0.17	0.04	0.04	0.50	0.18	0.09
LH2TT	0.8	0.8	0.19	0.03	0.03	0.44	0.20	0.11

Since on average at the perimeter of the calculated area, 50% of people present can be expected to be fatally exposed with higher percentage closer to the source and lower outside the area, it can be proven that if the fraction killed decreases exponentially with distance from the risk source, the number inside the 50% distance line is equal to that outside. Given a homogeneous population density, the product of the sum of the respective 50% lethality area distributions each multiplied by their respective ignition probability will result approximately in the distribution of total number of people killed. The final arc operation after multiplication of the total area with population density and with a mean materiel damage factor is multiplication with the expected event frequency to derive the distribution of number of fatalities and of damage in monetary units, all expressed on an annual basis.

Calculation of indicators of risk to people and valuation of the damage distribution in monetary terms is made here for illustrative purpose only. Urban population density was assumed to be 4000/m^2, and structural materiel damage has somewhat arbitrarily been set at \$1000/m^2 within the 50% lethality contour. Refining this level would require discriminating various sectors with different population densities and a detailed study of a variety of assets as a function of distance to the risk source. It is not that the model is not suited for such a calculation: the nodes can be easily expanded, but collecting data with a certain confidence is quite an effort, which is justified when a concrete location is examined. Human loss of life is controversial and can be valued from very different perspectives. For this study a value of life is arbitrarily chosen as causing a financial damage of M\$ 2 per individual, which is at the low side, see e.g., [14].

The discretized distributions (which can be copy/pasted to Excel spreadsheet) can be used to derive the societal or group risk values and an individual risk level contour of, e.g., 10^{-6}/yr around the risk source of a refueling station or at the location of a transportation accident. For group risk, the various effect area distributions that represent in principle all individual scenarios are multiplied with population density, ignition probability, and event frequency prior to summing. The resulting pairs of number of fatalities, N, and frequency, f, are ordered from low to high in number, and the frequency values are accumulated from the largest number of fatalities upwards to produce frequency F-values of exceeding N or more fatalities, which is plotted as a F-N curve. For the calculation of the individual risk distance value, the assumption is made that the probability of being killed by the event decreases exponentially with distance. From the contour radius, values derived from the discretized summed 50% lethality area distribution terms multiplied by the event frequency, by extrapolation along the exponential, the radius for each term at 10^{-6}/yr is found. Subsequently, the risk value at each radius is extrapolated to one at the largest radius found and the increments summed over the distribution. This produces a small correction increasing the largest radius found to yield the IR radius.

4. RESULTS

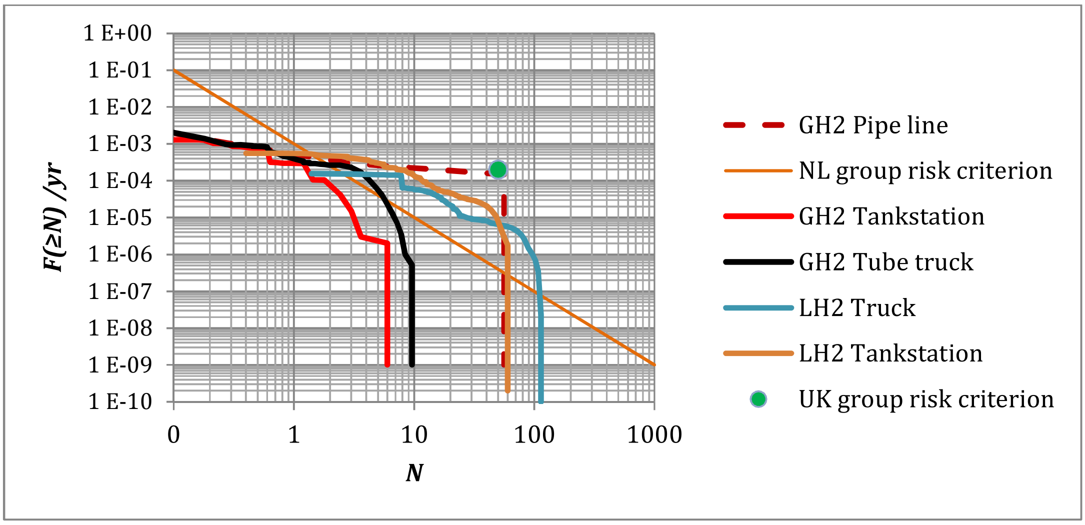

Figure 2. Societal risk F-N curves for the two refueling stations and the three transportation modes.

Table 4. Individual risk, IR distances and Expected Annual Loss, EAL results.

	IR 10^{-6}/yr Radius *m*	**EAL mean** *k$/yr*	**EAL st.dev.** *k$/yr*
GH2TS	16	2	5
GH2TT	21	3	7
GH2PL	34	15	21
LH2TS	67	14	17
LH2TT	70	7	7

In Figure 2 the societal risk results are presented as F-N curves and in Table 4 the 10^{-6}/yr individual risk contour distances. The societal risk of the LH2 as well as the pipeline are above the Dutch orientation norm (which starts at 10 fatalities or more) and just below the UK criterion point for intolerability of 50 fatalities or more in a single accident if expected frequency is more than 1 in 5000 years. All node calculation results in the form of a distribution can be inspected easily by clicking the nodes and viewing the results in the value tab as a histogram, probability density or cumulative density function. Changes can be made by clicking the definition tab.

The risk indicators in general point in the same direction: compressed hydrogen tank station and truck transport present the least risk, pipeline and liquefied hydrogen a much larger risk. This risk increase is due to the (assumed) possibility of a large vapor cloud explosion. The LH2 truck exposures are less frequent than the tank station, which despite its smaller maximum hydrogen mass stored is continually there and thus yields a larger expected annual damage but smaller individual risk.

The result of a risk assessment can be used in different ways:

- to investigate where main risks can be found so that preventive or protective risk reducing measures can be taken in concrete cases but also can be embodied in standards and codes
- to plan use of space (land use planning, LUP) or to obtain a license for an activity
- to help emergency response planning (which would benefit from information about expected numbers of injured persons)
- to perform business risk management and enable a cost-benefit analysis, CBA.

As regards CBA, several cost studies on hydrogen distribution have been made [15, 16]. These show a strong economy of scale effect for liquefied hydrogen reducing its costs to much lower levels than in case of compressed hydrogen. For very large quantities, pipeline distribution would be the best option. As often occurs, the more risky options are economically the most attractive. Expected annual loss (EAL) costs, which could be comparable to a risk insurance premium, remain however much lower than the distribution and delivery costs. A third mode of H_2 storage, namely absorbed as a hydride or otherwise, should be considered as economically promising. However, due to the many possibilities and lack still of a clearly preferred choice, the hazard properties are still fully open, and a risk assessment currently is not feasible. Comparison of hydrogen with natural gas as a fuel would be interesting as well.

5. UTILITY AND DECISION TREE FOR RISK GOVERNANCE

For decision making about LUP or licensing by a governing body, risk cost (EAL) should be translated into utility [17], a concept of relative desirability developed long ago in economics and financial risk management. This translation can take account of how numbers of fatalities and injured people as well as societal disruption are weighed against benefits for the ecology by using hydrogen as energy carrier in the economy. Most people are to a degree risk averse, which means that large consequences and high likelihood are disproportionately heavily weighed. Also, fatalities are weighed more heavily compared to economic damage. For a decision making purpose, utility (or here for risks ‘dis-utility’, having a negative value) shall be ‘calibrated’ against the set of preferences of the decision making governing body. In such case a plot of dis-utility versus risk produces a concave, e.g., quadratic curve of continuously increasing downward slope becoming asymptotic to infinite (dis-) utility. Risk aversion plays a major role in the shape of the curve: the higher the aversion the more negative the second derivative and hence the stronger the bending. It can also be shown that uncertainty appearing in equations as a value of standard deviation augments the aversion and increases the value of information for uncertainty reduction.

A discrete Bayesian Belief Net calculating disutility from costs and extended with a decision node of which the simplest form is shown in Figure 3 will support a decision process. In this net also, a sensitivity node is included to show the effect of uncertainty by introducing a high and low estimate.

This sensitivity test can be done at various input data. Unidentified scenarios and frequencies of an event belong to the largest uncertainties of a risk assessment (up to an order of magnitude). Effect studies are usually only off by a factor of 2, although in this case with large hydrogen spills due to lack of experience, uncertainty may be larger.

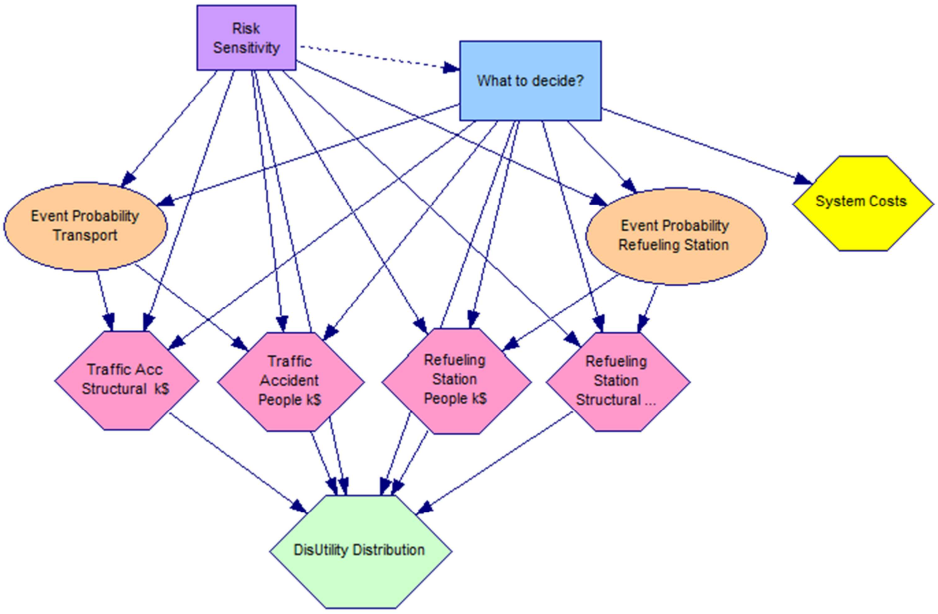

Fig. 3. Influence diagram in its simplest form provided with sensitivity node according to GeNIe [1].

An even clearer overview of options can be obtained when the data are arranged applying a decision tree [17], which can be drawn professionally using, e.g., the Precision Tree software of Palisade [19]. This software also uses the Excel sheet format, and it offers various forms of presentation of results, such as a risk profile of cumulative risk versus gains. In the decision the value of additional information by investing in tests to investigate the limiting conditions of a hydrogen cloud detonation can be included.

To bring the hazard perception of the various parties of stakeholders combined into one disutility ‘denominator’ will be not a simple task. Applying these tools will help to make matters more transparent, however, and show more objectively the effects of safeguard measures and alternatives. Though, stakeholder participation in decision making may be still far away from accepted practice.

6. UNCERTAINTIES AND PUBLIC PERCEPTION

A decision to build one tank station in a city in an experimental stage is relatively easy, but when one wants to develop a hydrogen economy, enlarging the scale, quickly quantities will become huge and, due to multiple risk sources in a region and a higher chance of an actual accident, public acceptance may become more difficult. Quite often there are conflicting opinions about acceptability of the risk of a particular project, and not all stakeholders involved have a common (economic) interest, or at least don’t feel such interest. Usually citizens living in the vicinity do not feel the urge of the project and oppose a go-ahead, or even if they see the need, it is the NIMBY or not in my backyard attitude that prevails. Not so much a low frequency outcome but a potential of a catastrophic consequence dominates risk perception, and uncertainties are brought to bear to resist positive decision. All that stirs up emotions, media turmoil, complot theory, and mistrust!

France defined separate classes of probability and consequence severity, which for coping with uncertainty for a certain case offers the possibility to express these quantities as orders of magnitude and not as numerical values, while the criteria in view of self-rescue are different for phenomena that unfold rapidly or slowly. In the Netherlands for LUP and license issuing, a QRA determining individual risk contours and societal risk is required by law, and performance of the QRA is not entrusted to a central expert body but left to market parties. Variability in QRA outcome is kept as small as possible due to prescribing the use of a standardized QRA model and data at the cost of flexibility and detail. Performing consultants are obliged to follow a course in using the model. Also, since the analysis assumes a standard level of safety performance, industry from a QRA point of view has no incentive to improve despite the (soft) ALARA (as low as reasonably achievable) requirement. Taking measures to decrease risk contours was often 'rewarded' by expansion of a municipality towards a company's location and hence taking its safety space. Acceptability criteria are law-based, but even with all these measures, resistance to a decision can generate sufficient pressure so that a project despite fulfilling the legal criteria in the political arena is turned down. This was shown recently in a carbon dioxide storage project planned in a deep, previous natural gas reservoir under a town, for which the analysis results amply met legal requirements.

The International Risk Governance Council in Geneva issued a few documents [18] that are most helpful in risk management from the point of view of definition of concepts and guidance for selecting strategy and instruments in difficult cases of decision making in the public domain.

7. CONCLUSIONS

1. This paper discusses and demonstrates a new alternative method of performing a risk analysis that employs an acyclic digraph of nodes connected by arcs representing a spill scenario development and determination of damage effects by operations on probability distribution functions of continuous and discrete stochastic variables. Advantages of the method are flexibility to introduce effects of all kinds of variables and transparency. The latter is obtained by direct access to distribution results at each node. The approach could accommodate detailed effects of built-up environment, atmosphere, and geography if these effects are introduced as generalized input parameters.
2. Results are produced of hydrogen distribution and transportation risks by considering a refueling station and transportation modes with compressed and liquefied hydrogen. It is shown that on the large scale of a hydrogen economy, the more attractive liquefied option generates larger risks than the compressed option. The uncertainties in the input data, in particular with liquefied hydrogen, are however quite large, because there is little solid experimental evidence available on large scale releases.
3. Decision theory enables a more transparent approach by structuring the decision process and determining (dis-)utility on the basis of risks and benefits. Experience with public perception shows that uncertainties severely and negatively affect decision making in the public domain.

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