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Application of Bayesian Networks to Quantitative Assessment of Safety Barriers' Performance in the Prevention of Major Accidents

Valeria Villa*, Valerio Cozzani

LISES – DICAM, Alma Mater Studiorum – Università di Bologna, via Terracini 28, 40131 Bologna, Italy
valeria.villa4@unibo.it

Process plants are particularly subjected to major accidental events, whose catastrophic escalations, triggered by external factors and characterized by very high impact and low probability, can affect both workers and population in the nearby of a process facility, as well as assets and environment. In the context of major accidents prevention, control and mitigation, safety barriers are widely employed; nevertheless, concerning their quantitative assessment, only availability is generally accounted as a measure of their performances and a frequency-based approach is applied. Recent applications have highlighted the potential of Bayesian Networks, a graphical probabilistic method, in major accidents modelling and prevention. This contribution is aimed at applying Bayesian Networks to quantitative assessment of safety barriers' performance in the context of major accidents prevention within the process industry. The Bayesian approach will be compared with a conventional Event-Tree based one by the application to an illustrative case study, considering a major accident whose occurrence can be prevented by the action of several pertinent technical safety barriers. In the Bayesian approach, safety barriers performance has been assessed by means of specific gates, depending on barriers states and classification. An adequate number of final states has been considered. The conversion of the Event-Tree, key element of the conventional frequency-based approach, into a Bayesian Network has been performed, with the aim to test the ability of Bayesian Networks in representing possible events sequences. Indeed, the potentialities of the Bayesian approach in revising probabilities have been explored by means of two different techniques: probability updating and probability adapting. In probability updating, the information about one of the outcomes is used as an evidence, determining the most probable explanation, leading to that specific final state. In probability adapting, additional information during a time interval, in the form of accident sequence precursors, are inserted in the analysis, in purpose to revise safety barriers' performances and final events probabilities. The results of the case study will highlight the advantages of a Bayesian approach to safety barriers' performance assessment, proving that its application may eventually will turn into a more flexible and realistic analysis of major accidental scenarios, in comparison with conventional techniques.

1. Introduction

During the past years, several accidental events raised the attention toward the possible occurrence of cascading effects within chemical and process facilities. Cascading effects are catastrophic accidents triggered by external hazard factors, as domino effects, security threats and natural events. Despite their different causes, all these accidents share low probabilities of occurrence and very high impacts in terms of human, environmental and assets losses, both inside and outside facilities boundaries (Reniers and Cozzani, 2013). Indeed, safety barriers are widely applied, concerning domino and Natech accidents, as well as security barriers, concerning security-based accidents, in purpose to prevent, control or mitigate their occurrence. Therefore, quantitative assessment of barriers' performances takes on a major role in accidents modelling and prevention (Landucci et al., 2015). Dynamic risk assessment techniques have recently emerged within the process industry domain, due to their flexibility in mirroring systems changes over time and to their enhanced intuitiveness in the presentation of results (Villa et al., 2015). Among these techniques, Bayesian

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Networks, a graphical probabilistic method, is nowadays a promising and increasingly popular tool, suitable to cope with complex and uncertain situations (Ale et al., 2014). Despite several applications of Bayesian Networks have been carried out, none of them has been focused on the quantitative assessment of safety barriers' performance in major accidents prevention, within the process industry domain.
In the present contribution, a comparison between conventional and Bayesian methodologies for quantitative safety barriers' performance assessment will be presented. Therefore, quantitative safety barriers' performance assessment by means of Bayesian Networks will be tested to an illustrative case study.

2. Quantitative safety barriers' performance assessment in the process industry domain

2.1 Quantitative safety barriers' performance assessment by means of Event-Tree Analysis

2.1.1 Fundamentals of Event-Tree Analysis

At the present time, quantitative assessment of safety barriers' performance is largely based on Event-Tree Analysis, representing the right side of Bow-Tie diagram. Event-Tree is a probabilistic model that correlates a top event with its outcomes, or consequences. It illustrates, from a qualitative and quantitative perspective, the logical relationships present in the system and indeed, it helps understanding which safety barriers failures would escalate the top event to a certain consequence (De Dianous and Fiévez, 2006). The construction of an Event-Tree starts from the identification of credible scenarios, by means of past-accident data review (Delvosalle et al., 2006). Then, the identification and detailed description of pertinent safety barriers with respect to the specific operational context should be carried out. In this phase, the relations among the elements present in the system should be investigated both qualitatively and quantitatively. In particular, the latter aspect aims at determining the performance of safety barriers. Generally, only the availability is accounted as a measure of safety barriers' performance (i.e., expressed by the probability of failure on demand – PFD). Eventually, the potential accident sequences and safety barriers' contributions are outlined by the calculation of consequences frequencies, or probabilities, according to the following equation:

$$f_{Cons\_i} = f_{Top\_Event} \cdot \prod_{i=1}^{n} PFD_i \qquad (1)$$

where f_{Cons_i} is the frequency of a final state i, obtained by multiplying the top event frequency (i.e., f_{Top_Event}) with the n failure probabilities of the safety barriers (i.e., PFD_i) leading to that consequence.
Recent applications stressed the importance of quantitative safety barriers' performance assessment, by means of Event-Tree based analysis, in the context of cascading effects prevention, regarding Natech accidents (Necci et al., 2014) and domino accidents (Landucci et al., 2015). Furthermore, the latter contribution proposed a novel approach to quantitative safety barriers' performance assessment that included specific gates, depending on barriers states and classification. According to the mentioned approach, the probability of a safety barrier failure is represented by a combination of availability and effectiveness. For instance, the performance of an active safety barrier can be described by the following expression (Landucci et al., 2015):

$$P_i = PFD_i + (1 - \eta_i) \cdot (1 - PFD_i) \qquad (2)$$

where P_i expresses the failure probability of a generic safety barrier i, by combining its availability, expressed as probability of failure on demand (i.e., PFD_i), and its effectiveness (i.e., η_i).

2.1.2 Limitations of Event-Tree Analysis

Despite the popularity of Event-Tree based approach within the process industry, the methodology shows several limitations. For instance, Event-Tree cannot include multi-state variables, cannot represent conditional dependencies and cannot apply real-time information from a facility to update prior "beliefs", which are prior probabilities of top events, intermediate events and safety barriers (Khakzad et al., 2013a). These limitations hinder from obtaining a real-time picture of safety barriers' performances and final consequences probabilities, therefore offering just a static risk picture, which is not able to account systems modifications and information derived from operational experience.

2.2 Quantitative safety barriers' performance assessment by means of Bayesian Networks

2.2.1 Fundamentals of Bayesian Networks

During the last decade, several efforts have been devoted to the development of dynamic risk assessment and related techniques, which can consider the dynamic evolution of conditions, both internal and external to the system (Paltrinieri et al., 2014). Among several existing approaches, Bayesian Networks (i.e., BNs) have emerged. Bayesian Networks (i.e., BNs) are graphical representations of uncertain quantities and decisions that explicitly reveal the probabilistic dependences among the variables and the related information flows. The most relevant advantage of BNs is that they provide a useful tool to deal with uncertainties and information from different sources, such as expert judgment and observable experience, being able to take into account common causes and influences of human factors as well (Ale et al., 2014).

In BNs, variables and their relations are represented by means of nodes and directed arcs; conditional probability tables (CPTs), assigned to the nodes, represent conditional dependencies. Therefore, according to Jensen and Nielsen (2007), under the assumption of conditional independence, a BN represents the joint probability distribution P(U) of variables U = {A_1, … , A_n}, as described by the following equation:

$$P(U) = \prod_{i=1}^{n} P\left(A_i | Pa(A_i)\right) \tag{3}$$

where Pa(A_i) is the parent set of A_i. Indeed, Bayesian Networks take advantage of Bayes theorem, which allows taking into account new evidences and consequently modifying probability distributions, by means of two different probability-revising techniques. In fact, Bayesian analysis can be performed through probability updating and probability adapting techniques. Probability updating consists in the calculation of the Most Probable Explanation, which is the most probable state of all the variables given the accident occurrence. Probability adapting consists in the calculation of posterior probability for a generic event x_i, given another event Q has occurred n times, which can be expressed in statistical terms as P (x_i | Q = n). Therefore, probability adapting means applying prior experience, in the form of cumulative information collected during a certain time span, named Accident Sequence Precursors (i.e., ASP), to adapt conditional probabilities distributions.

2.2.2 Conversion from an Event-Tree into a Bayesian Network

Some studies referred to process industries have recently compared and/or integrated Event-Tree analysis and Bayesian Networks (Khakzad et al., 2013a, 2013b), pointing out the advantages of Bayesian techniques. Therefore, the conversion process from an Event-Tree into a Bayesian Network becomes a crucial point.

Event-Tree mapping procedure into Bayesian Network, reported in Figure 1, is mainly based on the work of Bearfield and Marsh (2005), with subsequent modifications, referred to the process industry domain, implemented by Khakzad et al. (2013a). Each safety barrier of the Event-Tree is represented by a safety node having two states, one for the failure and the other for the success of the safety barrier; anyway, it is possible to consider multi-state variables. Indeed, a consequence node having as many states as the number of the event tree consequences (i.e., Cons_i) should be added to the network. When mapping an Event-Tree into a BN, a safety node i should be connected to the previous node i-1, only if the failure probability is conditionally dependent. In addition, there must be a connection between a safety node and the consequence node only if the probabilities of the states of the consequence node are influenced by the failure or the success of that safety node. After the BN is constructed, the probabilities of safety barriers are considered as the prior probabilities of safety nodes, and a conditional probability table is assigned to the consequence node, following an AND-gate logic model. CPTs for intermediate safety nodes are assigned, as simple causal relations. Then, the top event node should be connected to the safety barriers, according to the reasoning just explained, and to the consequence node. The latter assumption implies the definition of another final state (i.e., Safe state) to the consequence node; this additional state accounts the effect of the non-occurrence of the top event on the consequence node.

As discussed by Khakzad et al. (2013a), the conversion process highlights that each Event-Tree can be mapped to its corresponding BN, while a BN does not necessarily have an equivalent Event-Tree, due to multi-state variables and causal relationships other than simple Boolean functions such as OR-gates and AND-gates. For instance, the use of BNs makes it simpler to apply specific gates, as the one reported in Eq(2). Indeed, although able to consider the dependency of sequential safety barriers, an Event-Tree cannot capture the conditional dependency of safety barriers on the top event, while a BN accommodates such dependence by means of causal arcs drawn from the top event to the pertinent safety barriers.

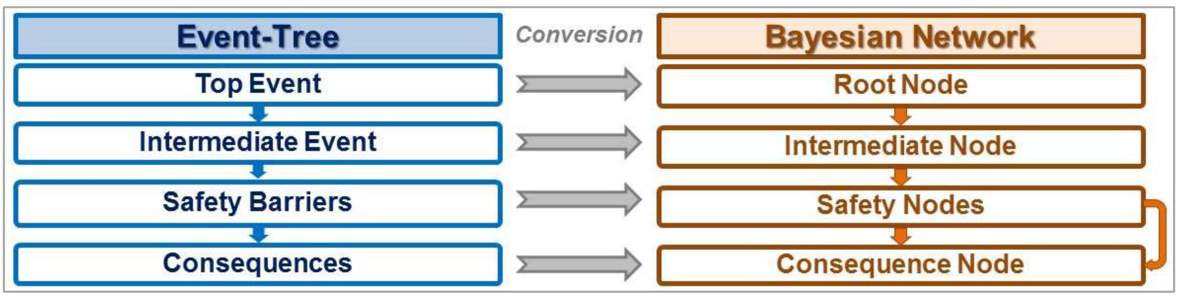

Figure 1: The conversion process of an Event-Tree into a Bayesian Network.

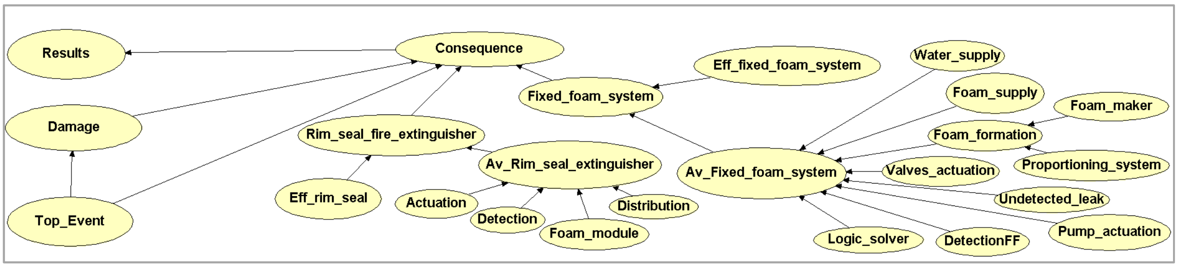

Figure 2: Bayesian Network obtained from Event-Tree conversion, regarding the prevention of a major accident (i.e., fire) by means of two pertinent safety barriers: rim seal fire extinguisher and fixed foam system.

3. Application of Bayesian Networks to quantitative safety barriers' performance assessment

Quantitative safety barriers' performance assessment by means of Bayesian Networks has been applied to an illustrative case study, regarding a major accident (i.e., fire), whose occurrence can be prevented or mitigated by the action of two pertinent technical safety barriers, a rim seal fire extinguisher and a fixed foam system. The conversion of an Event-Tree, adapted from Necci et al. (2014) has been performed and reported in Figure 2.

The top event is a lightning strike on an atmospheric storage tank, containing flammable liquid. The top event can determine either direct perforation or not, leading in the latter case to the action of the two active safety barriers. Indeed, the performance of safety barriers has been accounted by means of a specific gate, expressed by Eq(2), which combines availability and effectiveness. The availability (i.e., PFD) has been calculated for each barrier as the output of several pertinent subsystems. Indeed, for the effectiveness a reference value of 0.95 (Landucci et al., 2015) has been considered for both the barriers. According to this configuration, there are six possible consequences states, including state Safe. However, the most severe ones are Cons_1 and Cons_4, standing respectively for pool fire and full surface fire. Therefore, their sum, which a useful indicator of major accidents occurrence probability, has been considered as the final output of the BN, named for instance "Results". An overview on the data applied in the case study and on the most relevant outputs of Bayesian Network application has been reported in Table 1. Indeed, the application to the case study confirmed the equal ability of Bayesian Networks in the analysis of accidental scenarios, in comparison with the conventional Event-Tree based approach.

Table 1: Results of Bayesian Network application to a case study regarding major accident prevention

Symbol	Description	Probability	Type
Top_Event	Top event occurrence; lightning on storage tank	4.85E-02	Input
Damage	Intermediate event occurrence; probability of direct perforation	3.38E-04	Input
Av_Fixed_foam_system	Probability of failure on demand (PFD) for fixed foam system	7.01E-03	Output; OR-gate of 8 subsystems
Fixed_foam_system	Probability of fixed foam system failure (performance with combined PFD and effectiveness)	5.67E-02	Output; specific gate - Eq(2)
Av_Rim_seal_extinguisher	Probability of failure on demand (PFD) for rim seal fire extinguisher	2.38E-02	Output; OR-gate of 4 subsystems
Rim_seal_fire_extinguisher	Probability of rim seal fire extinguisher failure (performance with combined PFD and effectiveness)	7.26E-02	Output; specific gate – Eq(2)
Consequence	Consequence multistate node		Output; AND-gate
Cons_1	Release and pool fire	1.64E-05	
Cons_2	Rim seal fire extinguishment	2.55E-03	
Cons_3	Full surface fire extinguishment	3.32E-03	
Cons_4	Full surface fire	1.99E-04	
Cons_5	No consequences	4.24E-02	
Safe	Safe	9.52E-01	
Results	Fire probability	2.16E-04	Logic gate

Table 2: Accident Sequence Precursors (ASP) over five years of operational experience

Consequence	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
Cons_1	0	0	0	0	0	1
Cons_2	0	0	1	0	0	0
Cons_3	0	1	1	1	0	0
Cons_4	0	0	0	0	1	0
Cons_5	0	2	2	1	1	1

4. Results and discussion

Bayesian Network analysis has been performed by applying probability-revising techniques with a specific software.

The sequences of events leading to the two most critical final states (i.e., Cons_1 and Cons_4) have been determined by applying probability updating. For instance, the most probable sequence leading to Cons_1, with 84.4% probability, consists in the direct perforation of the tank, leading to release and pool fire. On the other hand, the most probable sequence leading to Cons_4, with 58.8% probability, is given by the availability and ineffectiveness of both safety barriers, leading to their failure and to full surface fire. Therefore, the importance of probability updating for safety barriers' performance assessment lies in its ability to identify critical sequence of events and allocate safety barriers consequently.

In probability adapting, fictional operational data over five years of experience, reported in Table 2, have been applied to revise top event, intermediate event, safety barriers' and consequences probabilities over time. Concerning both the safety barriers, their PFDs, as well as the failure probabilities of their subsystems, have been revised over time, showing a general increasing trend. Furthermore, their effectiveness values have changed consequently over time, with a general decreasing trend. Indeed, the application of a specific gate for the assessment of safety barriers' performances hindered from performances overestimation, in comparison with the standard approach based solely on PDFs. The results regarding the failure probabilities for both safety barriers, obtained by combining PFDs and effectiveness, have been reported in Figure 3. They show a global increase of the failure probability over time, which corresponds to a performance decrease over time, for both the rim seal fire extinguisher and the fixed foam system. Moreover, the insertion of ASP led to an increase after 5 years of the top event and intermediate event probabilities of one and two order of magnitude respectively. In addition, consequences probabilities show a general increasing trend over time, with the obvious exception of "Safe" state. The results of probability adapting referred to the most critical consequences (i.e., Cons_1 and Cons_4) have been reported in Figure 4. They show that the major accident probability (i.e., "Results" probability), either by release and pool fire or by full surface fire, increases after five years of more than two order of magnitude, revealing indeed a significant change in the relative percentages of the two final states. Therefore, probability adapting is a useful technique to replace generic prior probabilities (i.e., generic reliability data) with more case-specific posterior probabilities, resulting in a dynamic assessment of safety barriers' performance and a more reliable prediction of occurrence likelihood for each final event.

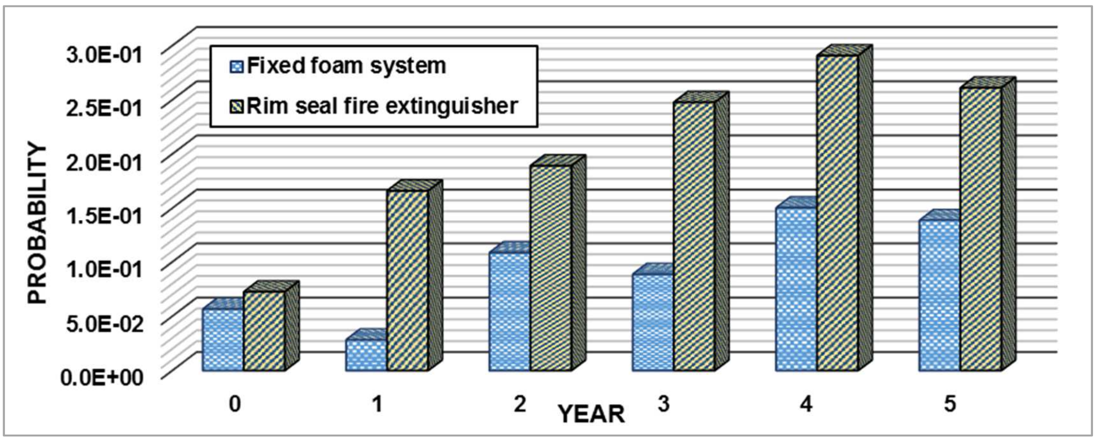

Figure 3: Safety barriers' failure probabilities over five years of operational experience by combined PFDs and effectiveness.

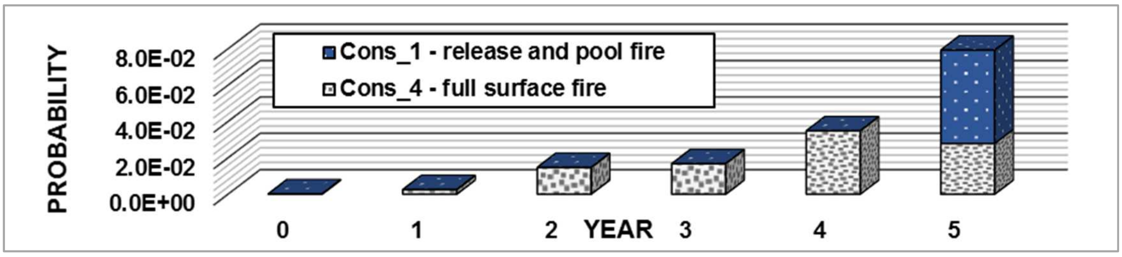

Figure 4: Major accident probability over five years of operational experience.

5. Conclusions

The current contribution has been aimed at comparing a conventional Event-Tree based approach with a Bayesian approach to safety barriers' performance assessment in the context of major accidents prevention. The advantages of Bayesian Networks application, in terms of enhanced flexibility and dynamic system representation, have been discussed. Therefore, BNs have been applied to an original case study, regarding a major accident that can be prevented by pertinent safety barriers. The case study demonstrated BNs ability to represent an accidental scenario, by the conversion of a previous Event-Tree based application. Furthermore, BN analysis, by means of probability updating and probability adapting, led to the revision of probabilities over time, showing that Bayesian technique may offer a more realistic assessment of safety barriers' performance and major accidents occurrence probabilities. Eventually, the results of the case study proved the applicability of Bayesian Networks in the context of safety barriers' performance assessment with respect to major accidents prevention in chemical facilities, which may be extended to cascading effects.

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