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Multi-perspective risk assessment using AHP and Bayesian Networks in process industries

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Abstract

In this paper, we develop a novel hybrid risk assessment (RA) methodology from different perspectives for a city gate station (CGS) in process industry. By being a hybrid RA method, we mean that the mostly human based safety risks assessment needs to be integrated into other important facets of risks in a process industry, e.g., material, equipment, assets, nature, security, etc. We also think that such a hybrid RA method should be taken from different relevant perspectives, as RA from a single perspective is ill defined, at least in a process industry. Further, two computing-competing vehicles of the analytic hieratical process (AHP) and Bayesian network (BN) are employed in this paper concurrently to see how they perform realizing the fact that the latter is more an advanced method requiring stronger expertise, while the former is simpler.

Keyword: Analytic hierarchy process (AHP); Bayesian networks (BNs); City gate station (CGS); Health-Safety-Environment (HSE); Multi-perspective; Risk assessment & Management.

Introduction

Risk assessment (RA) methods, which are established since the 1960s, are practical tools to reduce the occurrence probability, analyze potential risks, and estimate the severity of the consequences [1]. Any RA method composed of three steps of 1) hazard identification, 2) cause and consequence modeling, and 3) risk analysis. The results of RA are fundamental for mitigating risk potentials and establishing safety risk barriers. It can also be extended by the maintenance planning decision step to develop the risk-based maintenance (RBM) methodology, which is very fruitful in process industries.

There is a variety of techniques and methods for risk assessment such as risk matrix, failure mode and effect analysis (FMEA), hazard and operability study (HAZOP), fault tree analysis (FTA), event tree analysis (ETA), Bow-tie diagram (BT), analytic hierarchy process (AHP), Bayesian Network (BN), etc. [2].

Zarei et al. [3] developed a RA methodology based on an FMEA for hazard identification, a Bow-tie diagram for cause and consequence modeling, and a Bayesian network (BN) for risk analysis, and applied it to city gate stations. Also, Zarei et al. [4] developed a different RA methodology by applying HAZOP at the hazard identification step, ETA, FTA, and BT at the second step, and BN at the risk analysis step.

Leoni et al. [5] proposed an RBM methodology by applying risk matrix, FTA, and BNs to find maintenance time at different risk levels for a city gate station.

Rafiee et al. [6] combined Dempster-Shafer evidence theory (DST) with FMEA to hazard identification and prioritization. In Table 1, current studies for city gate stations are summarized stressing the fact that all current works are from a single perspective, while we pursue a multi-perspective approach for the first time in analyzing risks associated with a CGS.

Table 1. Risk assessment literature

Ref.	Perspective	Techniques	Software
[3]	Single	BT, FMEA, BNs	GeNIe
[4]	Single	ETA, FTA, BT, HAZOP, BNs	PHAST, GeNIe
[5]	Single	FTA, BNs	OpenBugs
[6]	Single	FMEA	-
This paper	Multi	FTA, BNs, AHP	Expert choise, Top Event FTA, GeNIe

This research aims to develop a hybrid RA methodology using both AHP and BNs methods from different perspectives. In order to verify the applicability of the developed methodology, a city gate station (CGS) is considered to be investigated as a case study. Thus, the key contributions of the present work, which are presented for the first time within the extant literature, are:

- We assess risk from different perspectives, i.e., perspectives of key stakeholders, as we consider RA from a single perspective is not viable in practice for process industries.
- Although, safety risk is a critical element in any RA exercise, our methodology considers other facets of risks as well, hence achieving a hybrid approach.
- We employ AHP and BNs at the same time to see how these methods perform with different levels of complexity, in order to help the industries to pick the right one.

Brief introduction on applied methods

Analytic Hierarchy Process (AHP), is a one of the most popular tools for multiple criteria decision making to the pair-wise comparisons, which applied during decades in different fields such as best alternative selection, optimization, resource allocation, planning, and etc. It calibrates quantitative and qualitative measures via the numeric scale which ranges from 1 to 9 based on their importance levels. The main steps of AHP are as follows [7]: 1. Problem definition. 2. Identify actors, outcomes, and objectives. 3. Define the criteria. 4. Construct a hierarchical structure by considering objectives, criteria, sub-criteria, and alternatives. 5. Perform pair-wise comparison and calibrate elements based on the scale. 6. Compute the maximum Eigen and normalized values for alternatives and criteria. 7. Repeat this procedure to find satisfying values.

A Bayesian network (BN) is a probabilistic directed acyclic graph with random system variables as nodes, and conditional dependency (cause-effect relationship) among connected nodes as arcs.

The probability distribution of each node (child node) as the component of a system is related to its parent nodes and represents the state of the component. The full joint probability distribution of a set of n random variables $A_1, A_2, \dots, A_n$ based on BN can be calculated using Equation (1).

$$P(A_1, A_2, \dots, A_n) = \prod_{i=1}^{n} P\big(A_i \big| Parents(A_i)\big) \quad (1)$$

Where $Parents(A_i)$ represents the set of parent nodes of node A_i.

The proposed methodology

The aim in a multi-perspective approach is that different stakeholders are engaged in a risk assessment process who have their own specific attitudes and needs. In a CGS, for example, we have found that at least 12 stakeholders are playing roles including company's top management, government authority, environmental agency, insurance company, United nations agency, and else. Even within a CGS itself managers, operators, contractors, visitors do not experience risks at the same doses. People living in the neighborhood who may suffer from the explosions and pollutions are also an important stakeholder one cannot ignore. Top managements who are concerned about the risks inflicted to the environment are different from the ones who do not care. Thus, an identical CGS in a certain area will produce different risks with respect to whom is the stakeholder. Even the risks induced internally due to bad operations or failures are different from the risks generated externally by heavy rains, flood, cyber-attacks, sabotages or riots. Top management will be plunged into great difficulties if risks from different players are not taken into considerations. For these reasons are that we consider that a multi-perspective RA method should be adopted instead. Holding a perspective is essential in performing root cause and consequence analysis, i.e., necessary for turning a qualitative risk factor into a quantitative risk measure.

After identifying the causes of risk, to show the relationship between the causes, the fault tree (FT) diagram is drawn according to Figure 1.

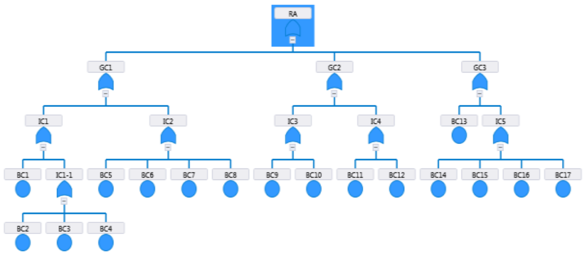

Fig. 1. Fault tree (FT) for risk assessment

Also, Table 2 shows description to explain general causes, intermediate causes & basic causes in FT.

Table 2. Causes in FT

Symbol	Description	Symbol	Description
GC1	*Human based risk*	BC6	air attack
GC2	*Material / Energy & equipment based risk*	BC7	theft & intentional error
GC3	*Natural based risk*	BC8	chaos, riots & strikes
IC1	*Human error*	BC9	*Aging failure (wear)*
IC1-1	*Operational Error*	BC10	Random failure
IC2	*Sabotage*	BC11	Type
IC3	*Equipment*	BC12	Amount
IC4	*Materials / Energy*	BC13	Temperature drastic changes
IC5	*Natural harsh events*	BC14	Earth movement
BC1	*Design error*	BC15	Heavy rain/Floods
BC2	Managerial error	BC16	Lightning
BC3	Operator error	BC17	High winds

BC4	Bad maintenance implementation error	B C5	cyber attack

According to the causes of risk and the consequences of risk, the comprehensive model of risk assessment using BNs is shown in Figure 2.

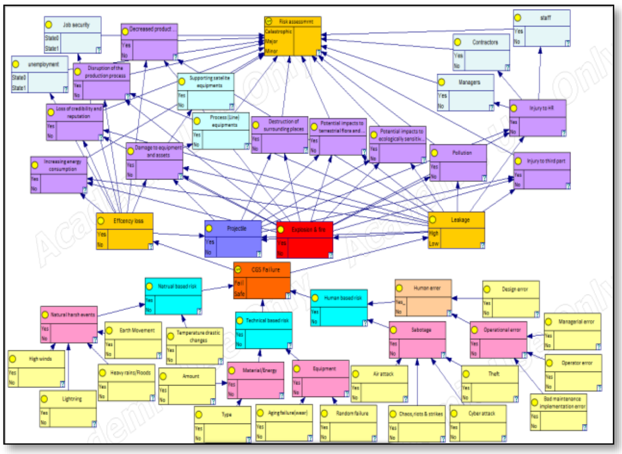

Fig. 2. BN comprehensive model of risk assessment

Also, the comprehensive model of risk assessment using AHP in Phase1 and Phase2 are shown in Figure 3 and Figure 4.

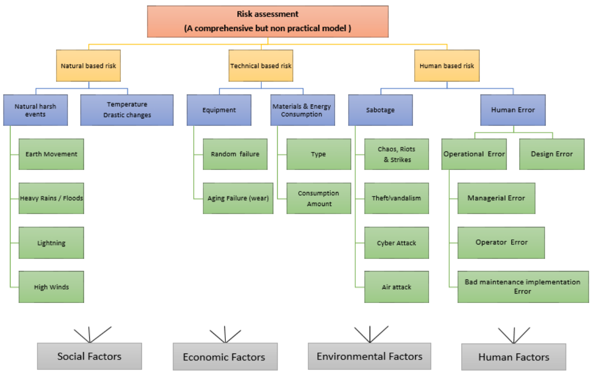

Fig. 3. Causes in AHP risk assessment model in phase 1

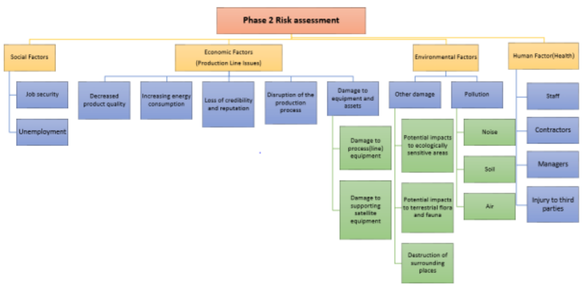

Fig. 4. The consequences in AHP risk assessment model in phase 2

Computational experiments

A city gate station (CGS) is a system to regulate and reduce gas pressure installed outside a city's limits. The CGS supplies gas at the required pressure to the city consumers. Figure 5 illustrates the location of a CGS in gas supply chain, and Figure 6 shows a schematic view of a typical CGS.

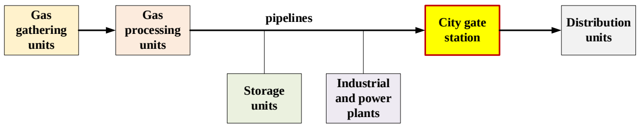

Fig. 5. The location of a CGS in Gas supply chain

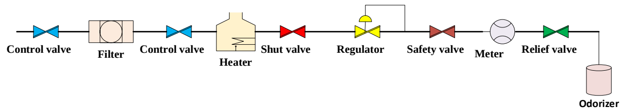

Fig. 6. A schematic view of a typical CGS

Here, we investigate risks incurs to a CGS from 12 different perspectives, i.e., Company (with environmental concern), Company (without environmental concern), Insurance, People in the neighborhood, Human resources (HR), Equipment & Machinery, Environment, Internal risk, External risk, Government, UN agencies, Neighboring countries.

We applied two methods for risk assessment. The first method is AHP that applied in two phase with considering causes and consequences. The second method is BNs which is modelled based on fault tree analysis. Finally we comapered the results obtained based on these two methods.

The comparative results of the two methods for the proposed perspectives are given. In order for the results of the BN to be comparable with the AHP, the obtained values have been normalized.

The results of risk assessment with two methods (AHP, and BNs) from the twelve perspective are compared in Table 3 to Table 14.

Conclusion

In this paper, we considered three main goals. First, the stakeholders' viewpoints were considered to have a comprehensive view of assessing the risks in process industries. Then two main safety and security major concerns are listed to analyze all root causes. Finally, the performance of two risk assessment techniques with different complexity levels was investigated for a city gate station risk assessment as a case study.

The results show that both of these techniques are practical for risk assessment in process industries.

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Table 3. Risk assessment results for the company with environmental concerns perspective

	Human Factors				Environment Factors				Economic Factors (Production Line Issues)					
Method	**Staff**	**Contractors**	**Managers**	**third parties**	**Potential impacts to ecologically sensitive areas**	**Potential impacts to terrestrial flora and fauna**	**Destruction of surrounding places**	**Pollution**	**Damage to process(line) equipments**	**Damage to supporting satellite equipments**	**Disruption of the production process**	**Loss of credibility and reputation**	**Increasing energy consumption**	**Decreased product quality**
AHP	0.0897	0.1021	0.0382	0.01911	0.00726	0.01662	0.0190	0.086	0.13467	0.06724	0.1214	0.11259	0.09121	0.1019
BN	0.088	0.09029	0.0451	0.03612	0.02935	0.02483	0.0225	0.0586	0.13093	0.09707	0.1196	0.10609	0.08352	0.0677

Table 4. Risk assessment results for the company without environmental concerns

	Human Factors				Economic Factors (Production Line Issues)					
Method	**Staff**	**Contractors**	**Managers**	**third parties**	**Damage to process(line) equipments**	**Damage to supporting satellite equipments**	**Disruption of the production process**	**Loss of credibility and reputation**	**Increasing energy consumption**	**Decreased product quality**
AHP	0.11024	0.12084	0.03339	0.15736865	0.078566	0.141855	0.131565	0.106575	0.11907	0.11024
BN	0.106267	0.108992	0.054496	0.15803815	0.117166	0.144414	0.128065	0.100817	0.081744	0.106267

Table 5. Risk assessment results from the perspective of the insurance industry

	Human Factors				Economic Factors (Production Line Issues)	
Method	**Staff**	**Contractors**	**Managers**	**third parties**	**Damage to process(line) equipments**	**Disruption of the production process**
AHP	0.124285	0.14137	0.04288	0.026465	0.443555	0.221445
BN	0.1777778	0.1822222	0.0711111	0.0622222	0.266666667	0.24

Table 6. Risk assessment results from the perspective of people in the neighborhood

Method	Explosion and fire	pollution	projectile
AHP	0.415	0.442	0.143
BN	0.4167	0.35	0.233

Table 7. Risk assessment results from the perspective of human resources

Method	Contractors	Staff	Managers
AHP	0.43	0.422	0.148

BN	0.412371	0.42268	0.164948

Table 8. Risk assessment results from the perspective of equipment and machinery

Method	Damage to process(line) equipments	Damage to supporting satellite equipments
AHP	0.667	0.343
BN	0.574257	0.425743

Table 9. Risk assessment results from an environmental perspective

Method	Potential impacts to ecologically sensitive areas	Potential impacts to terrestrial flora and fauna	Pollution
AHP	0.204	0.22	0.576
BN	0.218182	0.272727	0.509091

Table 10. Risk assessment results from the perspective of internal factors

	Human Factors				Environment Factors				Economic Factors (Production Line Issues)					
Method	**Staff**	**Contractors**	**Managers**	**third parties**	**Potential impacts to ecologically sensitive areas**	**Potential impacts to terrestrial flora and fauna**	**Destruction of surrounding places**	**Pollution**	**Damage to process(line) equipments**	**Damage to supporting satellite equipments**	**Disruption of the production process**	**Loss of credibility and reputation**	**Increasing energy consumption**	**Decreased product quality**
AHP	0.0819	0.0932	0.0349	0.0174	0.00675	0.01546	0.0177	0.0800	0.14109	0.07044	0.1271	0.11796	0.09555	0.1067
BN	0.0872	0.0917	0.0447	0.0357	0.029083	0.02460	0.0223	0.0581	0.13199	0.096197	0.1208	0.10514	0.08277	0.0693

Table 11. Risk assessment results from the perspective of external factors

	Human Factors				Environment Factors				Economic Factors (Production Line Issues)					
Method	**Staff**	**Contractors**	**Managers**	**third parties**	**Potential impacts to ecologically sensitive areas**	**Potential impacts to terrestrial flora and fauna**	**Destruction of surrounding places**	**Pollution**	**Damage to process(line) equipments**	**Damage to supporting satellite equipments**	**Disruption of the production process**	**Loss of credibility and reputation**	**Increasing energy consumption**	**Decreased product quality**
AHP	0.0957	0.1088	0.0407	0.0203	0.007316	0.01675	0.0191	0.0867	0.13103	0.065419	0.1181	0.10954	0.08874	0.0991
BN	0.1006	0.1041	0.0486	0.0347	0.027778	0.02430	0.0208	0.0555	0.14583	0.107639	0.0937	0.10416	0.06944	0.0625

Table 12. Risk assessment results from the perspective of the government

Method	Human Factors	Potential impacts to ecologically sensitive areas	Potential impacts to terrestrial flora and fauna	Destruction of surrounding places	Pollution	Increasing energy consumption	Decreased product quality	Job security	unemployment
AHP	0.40376	0.009004	0.020619	0.023603	0.0672	0.1685	0.1685	0.055	0.055

BN	0.42446	0.043165	0.046763	0.057554	0.097122	0.111511	0.172662	0.043165	0.003597

Table 13. Risk assessment results from the UN perspective

Method	**Human Factors**	**Environment Factors**	**Economic Factors**
AHP	0.4	0.365	0.235
BN	0.3984375	0.3671875	0.234375

Table 14. Risk assessment results from the perspective of neighboring countries

Method	**soil pollution**	**air pollution**
AHP	0.271	0.729
BN	0.16667	0.8333

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