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Dynamic risk assessment of CNG stations using the Bow-tie approach and Bayesian network

Dynamiczna ocena ryzyka w przypadku stacji CNG z wykorzystaniem podejścia Bow-tie i sieci bayesowskiej

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ABSTRACT: Today, CNG refueling stations are expanding worldwide to provide vehicles with CNG as fuel. However, constructing CNG stations in urban areas has led to serious threats to public and property safety. Therefore, risk assessment in these locations is essential. In most cases, risk assessment is the most complex part of risk management. While static methods, such as the Bow-tie approach, pose major limitations to most conventional risk assessment methods, dynamic risk assessment offers a better picture of risks and their consequences. This study aimed to develop a dynamic and comprehensive quantitative risk analysis (DSQRA) approach to evaluate accident scenarios and model risks in CNG stations. In this approach, FMEA was used for hazard analysis, while a Bow-tie diagram and Bayesian network were employed to model the worst-case accident scenario and assess risks. According to the results, dispenser gas leakage was identified as the worst-case accident scenario, with hose cracking and corrosion being the most critical factor. Therefore, in the risk management of CNG stations, priority should be given to the most probable basic events and main contributing factors identified in this study to reduce the likelihood of accident scenarios and thus mitigate risks.

Key words: dynamic risk assessment, Bayesian network, Bow-tie approach, CNG station.

STRESZCZENIE: Stacje CNG są obecnie budowane na całym świecie w celu dostarczania paliwa dla pojazdów napędzanych sprężonym gazem ziemnym. Jednak budowa stacji CNG na obszarach miejskich stwarza poważne zagrożenia dla bezpieczeństwa osób i mienia. W związku z tym niezbędne jest przeprowadzenie oceny ryzyka dla tych miejsc. W większości przypadków ocena ryzyka jest najbardziej złożonym aspektem zarządzania ryzykiem. Metody statyczne, takie jak podejście *Bow-tie*, stanowią wyraźne ograniczenia dla większości konwencjonalnych metod oceny ryzyka, natomiast dynamiczna ocena ryzyka oferuje lepszy obraz zagrożeń i ich konsekwencji. Celem niniejszego badania jest opracowanie dynamicznej i kompleksowej ilościowej analizy ryzyka w celu dokonania oceny scenariuszy wypadków i modelowania ryzyka na stacjach CNG. W tym podejściu do analizy zagrożeń wykorzystano FMEA, a do modelowania najgorszego scenariusza wypadku i oceny ryzyka zastosowano diagram *Bow-tie* i sieć bayesowską. Wyniki wskazują, że najgorszym scenariuszem jest wyciek gazu z dystrybutora, a najbardziej krytycznym czynnikiem jest pękanie i korozja węża. Dlatego też w zarządzaniu ryzykiem na stacjach CNG w celu zmniejszenia prawdopodobieństwa wystąpienia wypadków, a tym samym ograniczenia ryzyka, w pierwszej kolejności należy uwzględnić najbardziej prawdopodobne podstawowe incydenty i główne czynniki przyczyniające się do ich wystąpienia, zidentyfikowane w ramach niniejszych badań.

Słowa kluczowe: dynamiczna ocena ryzyka, sieć bayesowska, podejście *Bow-tie*, stacja CNG.

Introduction

Natural gas is a clean, economical, and environmentally beneficial energy source with numerous applications in today's society (Chamberlain and Modarres, 2005; Khan et al., 2015; Wu et al., 2017). It is primarily composed of methane, which is colorless, tasteless, odorless, lighter than air, and disperses quickly, though it is highly flammable and explosive (Parvini and Kordrostami, 2014; Wu et al., 2017). A methane-air mixture of 4.5 to 16.5 percent is flammable and explosive, with an ignition energy of 280 micro Joules (Berghmans and Vanierschot, 2014). Natural gas also contains hydrocarbons, carbon dioxide, nitrogen, and hydrogen sulfide in various proportions (Bhattacharjee et al., 2010; Tang et al., 2014). Methane can be

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used as a compressed fuel for vehicles (Bhattacharjee et al., 2010). Today, more than 18 million natural gas vehicles operate in more than 86 countries, with high concentrations in Iran, China, Pakistan, Argentina, India, Brazil, Italy, the United States, New Zealand, and Colombia (Bhattacharjee et al., 2010; Khan et al., 2015). In addition, there are over 26,677 CNG filling stations worldwide (Khan et al., 2015).

Given their location in urban areas, CNG stations present a significant safety concern due to the potential hazards they pose in cities (Nouri et al., 2010). The consequences of damage to these systems, whether accidental or intentional, can be catastrophic (Zarei et al., 2017b). Thus, the safety of public has been a major concern since the commercial use of compressed natural gas (CNG) as a new type of vehicle fuel began (Han and Weng, 2011; Parvini and Kordrostami, 2014). Given specific characteristics of the natural gas (high flammability, explosiveness, and dispersion), accidents of at CNG stations differ from other industrial accidents (Han and Weng, 2011). For example, records from Korea show 41 CNG station accidents from 1992 to 2003, 25 of which (61%) were fires and explosions, with one incident resulting in damages estimated at 13 million dollars (Park et al., 2006). In 2004, a NG plant explosion in Belgium caused 14 deaths and injured more than 200 people. In the same year, the explosion in Paraguay led to more than 250 deaths, and an explosion in Moscow in 2009 caused by gas leakage led to the largest conflagration in recent history (Khan et al., 2015). On August 10th, 2008, heavy explosions occurred at the propane gas storage facility in Toronto, leading to death of two and evacuation of thousands of people (Kalantarnia et al., 2009). According to statistics, 480 fires occurred in hazardous areas like CNG stations in Tehran from 2002 to 2006 (131 in 2004, 161 in 2005, and 184 in 2006) (Nouri et al., 2010).

Conducting safety analysis in gas processing facilities and risk assessment in places where large amounts of fuel (such as CNG, LPG, etc.) are stored is critical (Shebeko et al., 2007; Khan et al., 2015). To control and manage the risks in these settings, an appropriate risk assessment system is needed to evaluate risk levels and develop a systematic control program (Nouri et al., 2010). Risk analysis is an effective tool for developing accident prevention strategies and mitigation measures (Dormohammadi et al., 2014; Zarei and Mohammadfam, 2015). Quantitative Risk Assessment (QRA) is widely used in the industry to evaluate, analyze, and manage risk (Abimbola et al., 2015).

Several studies assessing safety hazards at CNG stations highlight issues with the performance of CNG tanks in vehicles and the lack of standardization (Bhattacharjee et al., 2010; Kim and Choi, 2013; Parvini and Kordrostami, 2014). Other studies have focused on static risk assessment at CNG stations (Badri et al., 2010, Yong and Sui, 2009). However, due to constant fluctuations in CNG station parameters, dynamic risk studies are essential.

Conventional QRA methods, such as fault tree, event tree, Bow-tie diagram, and risk determination, are typically static and thus cannot capture the dynamic risk of process hazards (Yang and Mannan, 2010; Khakzad et al., 2013; Abimbola et al., 2014). Bayesian Network (BN) is a widely used tool in industrial risk analysis (Khakzad et al., 2013), offering probabilistic inference technique for reasoning under uncertainty that can reduce the limitations of conventional methods and take into account conditional dependencies, common failures, and various basic event modes in accident modeling. The main advantage of BN is its ability to perform probability updating, which makes it an excellent approach to analyze the risk of dynamic systems (Li et al., 2016; Zhang et al., 2018). To address these limitations, this study employs a dynamic and comprehensive quantitative risk analysis (DCQRA) approach based on Bayesian network.

This study aims to highlight the importance of a dynamic and comprehensive approach in accident scenario modeling and risk analysis of CNG stations. In this approach, FMEA (failure mode and effect analysis) is applied for hazard analysis and identification of worst-case scenarios. The Bow-tie diagram is used for cause-consequence analysis of the worst-case scenario, while Bayesian network technique is employed to consider conditional dependencies and risk updating.

Method

Hazard analysis
FMEA

The failure mode and effects analysis (FMEA) technique is a powerful and effective analytical tool widely used in engineering projects to examine possible failure modes that could adversely affect overall system reliability. FMEA can incorporate the failure rates of each failure mode to achieve a quantitative probabilistic analysis. Additionally, FMEA can be extended to evaluate failure modes that may lead to an undesired system state, such as a system hazard, making it suitable for hazard analysis. When component failure rates are assigned to identified potential failure modes, the failure probability of a subsystem or component can be derived. This method has been expanded to determine the effects of failure conditions, but it can also be used to identify hazardous aspects of potential failure modes. Successful development of FMEA requires the analyst to include all significant failure modes for each contributing element or part in the system (Puente et al., 2002; Chen, 2007).

The information needed for FMEA includes task description, failure modes, failure causes, failure effects on the system, the severity of effects (S), the probability of failure (P), the detection level (D), and the risk priority number (RPN). RPN is calculated using Equation (1):

$$RPN = S \times P \times D \quad (1)$$

Bow-tie approach (accident scenario modeling)

BT is one the best graphical approaches for modeling an accident scenario, starting from causes and ending with consequences of the scenario. BT consists of a Fault Tree (FT) on the left side, a diagram with basic events, intermediate events, and top events connected by logic gates and transfer symbols. On the right side of the bow-tie model is the Event Tree (ET), which begins with a primary event —the top event of the FT —and is divided into two branches at each safety barrier, with one branch representing the operation of the safety barrier and the other its failure. Each branch represents a different sequence of events and terminates in a consequence. The bow-tie method can be used in both qualitative analysis and quantitative calculation (Khakzad et al., 2012, Khakzad Rostami, 2012; Cai et al., 2013). Qualitatively, BT provides a clear representation of the logical relationships among basic and intermediate events leading to a top event, illustrating how safety barrier failures can escalate the top event to accident consequences.

In the BT, quantitative evaluation of the FT part requires failure and/or occurrence probability of basic events. Given these data, several methods are available to evaluate the probability of the top event, including the minimum cut sets method, the gate-by-gate method, and Monte Carlo simulation (Lees, 2012). In quantitative analysis of the ET part, the occurrence probability of each consequence is calculated based on the failure (or success) probability of safety barriers.

BT has limitations in the risk analysis of large systems with common and dependent failures due to is reliance on static methods like FT and ET, which are not suited for dynamic risk analysis unless supplemented with other techniques, such as physical reliability models or Bayesian updating (Khakzad et al., 2012).

Bayesian Network

The use of Bayesian Network (BN) for industrial risk assessment is relatively new. Recently, BN has often been incorporated into FT and Bow-tie analyses (Khakzad Rostami, 2012; Khakzad et al., 2013; Abimbola et al., 2015). BN analysis has become a popular probabilistic inference approach for reasoning under uncertainty, showing the quantitative relationship between variables and allowing probability updates as a new information becomes available (Khakzad Rostami, 2012; Khakzad et al., 2012, 2013). This dynamic capability enables BN to overcome limitations of other risk assessment techniques. BN can also model conditional dependencies among various risk assessment approaches, including fault trees, event trees, and Bow-tie (Khakzad Rostami, 2012; Khakzad et al. 2013). BN includes both qualitative and quantitative components (Cai et al., 2013): the network structure represents the qualitative component, while conditional probabilistic distributions assigned to the nodes represent the quantitative component (Khakzad et al., 2013). In BN, each node in the graph represents a random variable, and the branches (arcs) denote probabilistic dependencies among variables.

In BN, Equation 2 is used to compute the probability distribution of a set of variables $U = \{X_1, ..., X_n\}$:

$$P(U) = \prod_{i=1}^{n} P\left(Ai \mid Pa(Ai)\right) \quad (2)$$

$Pa(Ai)$ – parent set of Ai in BN, while $P(U)$ – properties of BN (Khakzad et al., 2013; Abimbola et al., 2015).

In diagnostic analysis, BN uses Bayes theorem to update the prior probability of events based on new information, called evidence E. The posterior probability distribution can be calculated using various types of inference algorithms, such as the connection tree or variable elimination based on the Bayes theorem.

$$P(U \mid E) = \frac{P(U \mid E)}{P(E)} = \frac{P(U \mid E)}{\sum_U P(U \mid E)} \quad (3)$$

Sensitivity study

A sensitivity analysis was performed on both the BT and BN models in order to identify the most critical basic events and minimum cut sets (MCS) leading to the accident. The ratio of variation (RoV) was used to rank basic events and $MCSs$ based on their criticality. RoV is used to estimate the most critical basic event and $MCSs$ contributors to the top event (Zarei et al., 2017a). RoV is calculated using equations (4) and (5):

$$RoV(BE_i) = \frac{\pi(BE_i) - \theta(BE_i)}{\theta(BE_i)} \quad (4)$$

$$RoV(MCS_i) = \frac{\prod_{i \int MSC} \pi(BE_i) - \prod_{i \int MSC} \theta(BE_i)}{\prod_{i \int MSC} \theta(BE_i)} \quad (5)$$

where: $\pi(BE_i)$ and $\theta(BE_i)$ represent the posterior and prior probabilities, respectively.
$\prod_{i \int MSC} \pi(BE_i)$ and $\prod_{i \int MSC} \theta(BE_i)$ stand for the posterior and prior probabilities, respectively.

The determination of cut sets importance and the estimation of improvement index are used for sensitivity analysis

(Ferdous et al., 2007). Cut sets importance is calculated using Equation (6):

$$I^{C_i} = \frac{Q_j}{Q_O} \times 100 \quad (6)$$

where:
I^{C_i} – cut sets importance,
Q_j – cut sets frequency,
Q_O – top event frequency.

By removing each basic event from the tree and evaluating its weight on the tree, the improvement index identifies the most critical basic events leading to the top event (Lai et al., 1988; Ferdous et al., 2007).

Risk importance measures, including Risk Achievement Worth (RAW) and Risk Reduction Worth (RRW) were used in the sensitivity analysis to rank basic events based on their contribution to system failure (Aven and Nøkland, 2010).

CNG Stations Description

In general, the main components of the CNG filling stations are (Figure 1):
- Metering unit,
- Dryer,
- Compressor,
- Tanks,
- Dispenser.

The two main operations in the metering unit include the gas refinement and the measurement of the gas flow into the station. In this unit, the gas consumption of the station is measured by gas meter. After refinement in the metering unit, the gas enters the dryer, where moisture and impurities are removed. Next, the gas enters the compressor, which is typically a multi-stage reciprocating compressor with gas pressure reaching about 250 bars. Once compressed, the gas is sent to the storage tanks, which enhance the station's potential and capacity by storing natural gas. Finally, the dispenser transfers fuel from the station to the vehicle. Equipped with a control system, the dispenser regulates fuel injection and prevents overflow when the car tank reaches the desired pressure.

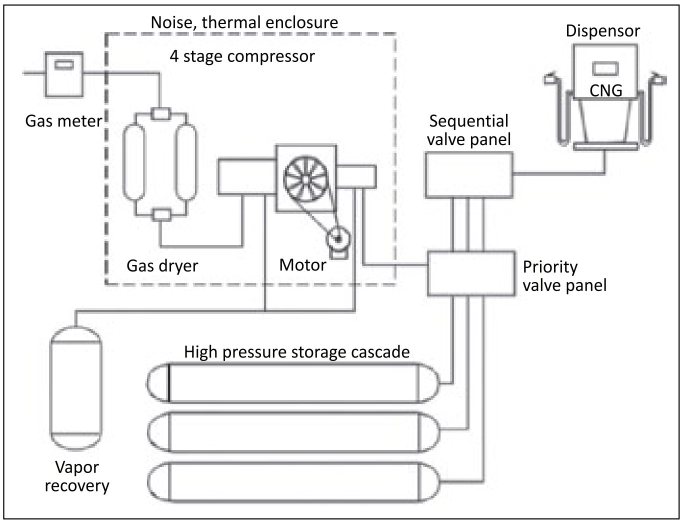

Figure 1. Components of a CNG station (Chinese et al., 2014)
Rysunek 1. Elementy składowe stacji CNG

Results

FMEA

Failure and its effects were identified in the CNG stations:
1. Hazard centers were identified.
2. A qualitative overview of hazard sources was developed, considering their function, failure modes, failure causes, and effects on the CNG station.
3. A quantitative hazard analysis was carried out by assigning severity (S), probability (P), and detection levels (D) to each hazard source to calculate the risk priority number (RPN) for each hazard.

The values of S, P, and D for each component's failure modes and effects were determined by a group of safety and process experts in the field. Table 1 presents the RPN for all hazard sources in the CNG stations.

As shown, dispenser gas leakage has the highest RPN in the CNG stations and is thus considered the worst-case accident scenario, warranting comprehensive and detailed risk analysis in this study.

Bow-tie Model of dispenser gas leakage

Analysis of Risk Factors and Fault Tree construction

Failure of the dispenser system refers to dispenser gas leakage and is defined as a critical event in the Bow-tie model. To evaluate the risk of dispenser gas leakage, the associated risk factors were first analyzed.

The main causes of dispenser gas leakage were identified through direct observation, expert interviews, and review of documents and operational maps. Five primary contributors were pinpointed, including tool control failure, dispenser hose rupture, high gas pressure, operator error, and pipeline system failure. These main factors were further broken down into basic and intermediate events, as depicted in Figure 2. Symbols, descriptions, and failure probabilities of the basic and intermediate events are presented in Tables 2 and 3. Symbols BE and IE indicate the basic and intermediate events, respectively (See Tables 2 and 3).

Table 1. RPN of all hazard sources (hazardous subsystems) in the CNG stations
Tabela 1. Liczby priorytetu wszystkich źródeł zagrożeń (niebezpiecznych podsystemów) na stacjach CNG

Failure mode	Cause	S	P	D	RPN
Dispenser gas leakage	Human error or instrument failure	6	4	2	48
Pipeline gas leakage	Mechanical failure/corrosion	5	4	2	40
Electrical equipment failure	Defective electrical cables/low resistance	5	3	2	30
Compressor performance malfunction	Compressor exhaust/ lack of proper and timely repair	5	3	2	30
Poor filtration	Use of inappropriate filters and lack of proper and timely repairs	3	4	2	24
Pressure switch failure	Mechanical failure	3	4	2	24
Trap failure	High gas pressure/ lack of proper and timely repairs	3	3	2	18
Dryer failure	Mechanical failure/failure of filter	3	3	2	18
Valves failure	High gas pressure/burnout/ lack of proper and timely repairs	3	3	2	18
Failure of flow meter	Mechanical failure	3	3	2	18
Overpressure/ failure of storage containers	Fill storage on cold day/high temperature environment	3	2	2	12
Metering unit failure	Flow meter failure/ lack of proper and timely repairs	3	2	2	12
Pressure gage	Mechanical failure/ lack of proper and timely repairs	2	2	2	8
Temperature gage	Mechanical failure/ lack of proper and timely repairs	2	2	2	8
Seels failure	Mechanical failure/ lack of proper e and timely repairs	2	1	2	4
Earthing failure	Mechanical failure/ lack of proper and timely repairs	2	2	1	4

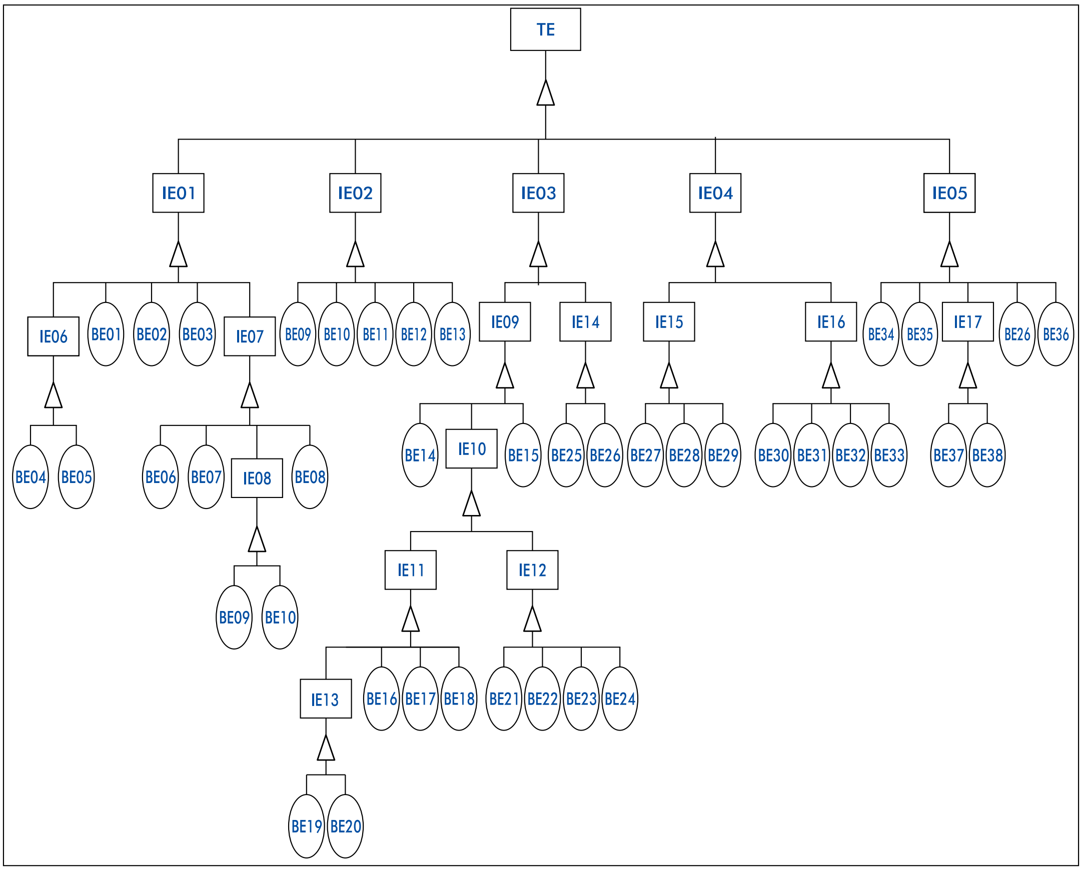

Figure 2. The fault tree of the dispenser gas leakage
Rysunek 2. Drzewo błędów dla wycieku gazu z dystrybutora

In this study, the occurrence probability of events was obtained from databases such as OREDA, expert opinions, data provided in the Risk Analysis Guide, the American Chemical Engineering Association (Guidelines for Chemical Process Quantitative Risk Analysis, 2000; Grossel, 2001), as well as from the data provided in the Study by Qinglei et al. (Tan et al., 2014).

Table 2. Description and failure probability of basic events of the FT
Tabela 2. Opis i prawdopodobieństwo wystąpienia usterek dla głównych zdarzeń drzewa błędów

Symbol	Description	Probability	Symbol	Description	Probability
BE01	Breakaway connection failure	1.62×10^{-3}	BE20	Cooling performance failure	1.03×10^{-3}
BE02	Reactor reel failure	1.29×10^{-3}	BE21	Pressure Switch	3.99×10^{-3}
BE03	Regulator performance failure	1.23×10^{-3}	BE22	Pressure Transmitter	3.04×10^{-3}
BE04	Sensor failure	3.06×10^{-3}	BE23	Pressure Indicator	2.53×10^{-3}
BE05	Transmitter failure	3.06×10^{-3}	BE24	Shut-off valve performance failure	1.08×10^{-2}
BE06	Lack of timely performance Excess flow valve	4.23×10^{-3}	BE25	Inappropriate connections	9.52×10^{-2}
BE07	Check valve failure	1.46×10^{-3}	BE26	Inappropriate filtering	1.23×10^{-2}
BE08	Butterfly valve failure	2.09×10^{-3}	BE27	Unusual operation	1.00×10^{-3}
BE09	Lack of proper and timely repair	5.00×10^{-3}	BE28	Selecting the same controller by mistake	2.00×10^{-4}
BE10	High pressure gas during fueling operations	5.62×10^{-3}	BE29	Mistake reading agenda or dispenser screen	1.60×10^{-3}
BE11	Terrorism	1.48×10^{-3}	BE30	Deliberate error in following the instructions	5.00×10^{-3}
BE12	Cracking and corrosion hose	1.24×10^{-2}	BE31	Incorrect risk assessment	9.42×10^{-3}
BE13	Car collision with nozzle	3.00×10^{-3}	BE32	Incorrect hazard assessment	1.34×10^{-3}
BE14	PRV failure	1.00×10^{-4}	BE33	Inadequate training	1.34×10^{-3}
BE15	PSV failure	1.00×10^{-4}	BE34	Inappropriate welding	9.96×10^{-4}
BE16	Temperature Switch failure	5.19×10^{-4}	BE35	Inappropriate installation	9.52×10^{-4}
BE17	Temperature transmitter failure	1.35×10^{-3}	BE36	Separators failure	9.75×10^{-4}
BE18	Normal thermometer performance failure	1.08×10^{-3}	BE37	Transmission system failure (external coating)	6.30×10^{-2}
BE19	Lack of dissipation by the tubes/Cartel enclosure	4.56×10^{-3}	BE38	Cathode cell defects	6.30×10^{-2}

Table 3. Description and failure probability of Intermediate events of the FT
Tabela 3. Opis i prawdopodobieństwo wystąpienia usterek dla zdarzeń pośrednich drzewa błędów

Symbol	Description	Probability	Symbol	Description	Probability
IE01	Control tools failure	2.20×10^{-2}	IE10	Compressor failure	1.97×10^{-2}
IE02	Hose tear	2.53×10^{-2}	IE11	Increased compressor compartment temperature	8.73×10^{-3}
IE04	High-pressure gas	1.97×10^{-2}	IE12	Inadequate pressure regulators	1.05×10^{-2}
IE04	Operator error	2.03×10^{-2}	IE13	Tube obstruction	5.58×10^{-3}
IE05	Flaws in the pipeline system	1.94×10^{-2}	IE14	Tube obstruction	1.17×10^{-4}
IE06	Meter flow performance Failure	9.36×10^{-4}	IE15	Incorrect implementation of work instructions	2.79×10^{-3}
IE07	Inappropriate valve operation	1.37×10^{-2}	1E16	Stress and haste during operation	1.70×10^{-2}
IE08	Sudden valve bursting	5.55×10^{-2}	IE17	Corrosion	3.96×10^{-3}
IE09	Pressure-reducing systems failure	1.96×10^{-2}			

Event Tree Analysis

Compressed natural gas leakage can lead to serious consequences. Natural gas is highly flammable and explosive. Safety barriers should be implemented to reduce dispenser gas leakage. Table 4 provides the symbols, descriptions, and failure probabilities of the ET's safety barriers (immediate ignition barrier (IIB), delayed ignition barrier (DIB), presence/absence of congestion (Cong), Ball Valve, and manual emergency shutdown (ESDm)). The success or failure of safety barriers can lead to 10 potential outcomes, as shown in Figure 3. Safety barrier probabilities were derived from the DNV databases (OREDA, 2002).

In the event tree, dispenser gas leakage is shown as the primary event. Table 5 provides detailed descriptions of the consequences of the dispenser gas leakage.

Bow-tie Model Construction

Figure 4 presents Bow-tie model of dispenser gas leakage, with the fault tree on the left and the event tree on the right.

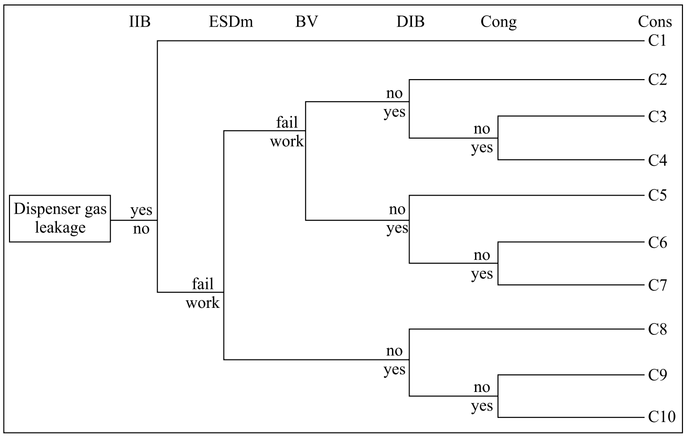

Figure 3. The event tree of the dispenser gas leakage
Rysunek 3. Drzewo błędów dla wycieku gazu z dystrybutora

Table 4. Failure probability of safety barriers in ET
Tabela 4. Prawdopodobieństwo awarii barier bezpieczeństwa

Safety barriers	Probability
IIB	0.10
DIB	0.60
Cong	0.60
BV	0.30
ESDm	0.33

Table 5. Consequence of the event tree
Tabela 5. Konsekwencje wynikające z drzewa błędów

Symbol	Consequences
C1	Jet fire, catastrophic property damage, high death toll
C2	Major release
C3	Flash fire, major property damage, possibility of fatalities
C4	Vapor cloud explosion (VCE), major propriety damage
C5	Moderate release
C6	Flash fire, moderate property damage
C7	Vapor cloud explosion (VCE), moderate propriety damage
C8	Minor release
C9	Flash fire, minor property damage
C10	Vapor cloud explosion (VCE), minor propriety damage

Bayesian Network modeling for dispenser gas leakage

Figure 5 shows the Bow-tie modelling of the dispenser gas leakage using the Bayesian Network (BN) model. An algorithm for mapping BT to BN proposed by (Khakzad et al., 2013) was utilized. In this study, BN was simulated and run in GeNIe 2.0 software (BayesFusion).

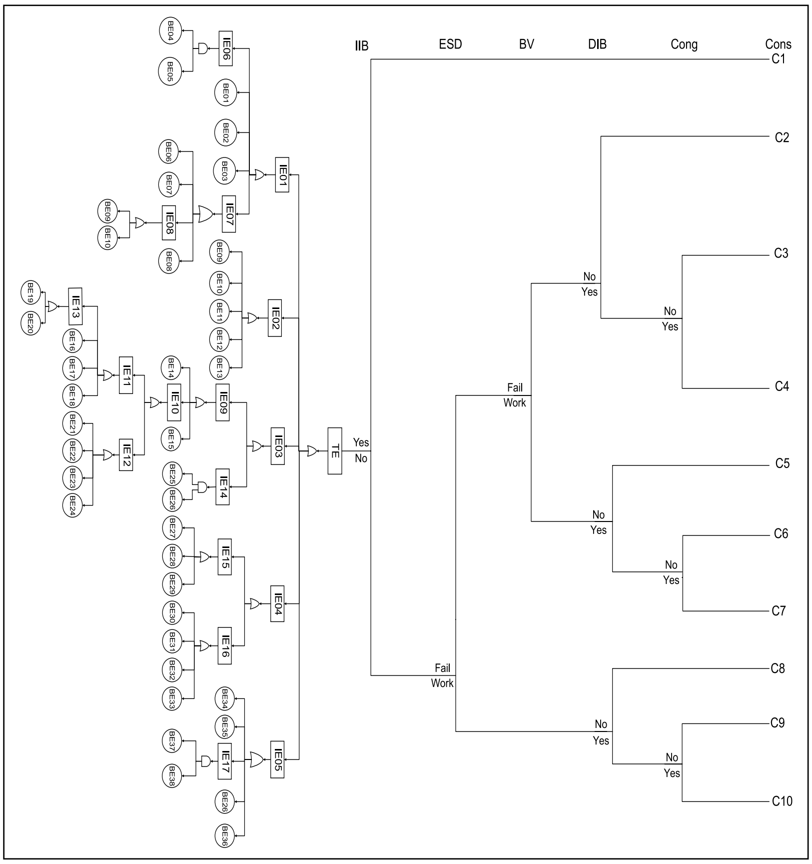

Figure 4. Accident scenario modeling of the dispenser gas leakage using Bow-tie approach
Rysunek 4. Modelowanie scenariusza wypadku wycieku gazu z dystrybutora przy użyciu metody *Bow-tie*

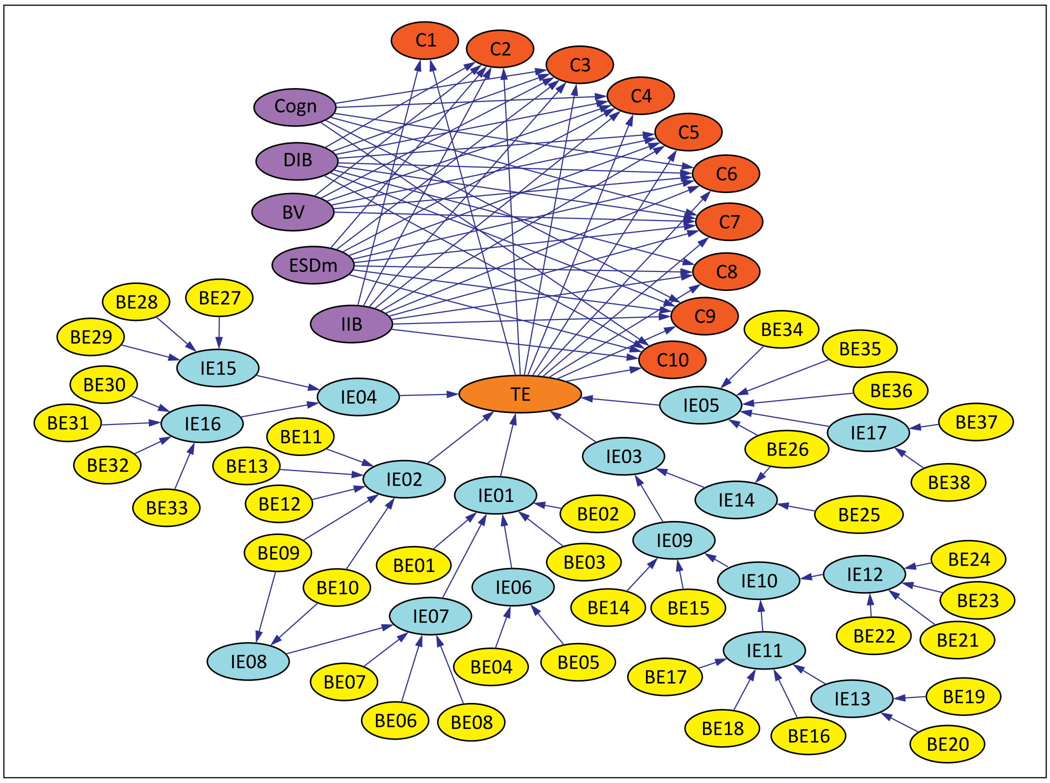

Figure 5. Dynamic cause-consequence analysis of the dispenser gas leakage using BN
Rysunek 5. Dynamiczna analiza przyczynowo-skutkowa wycieku gazu z dystrybutora z wykorzystaniem BN

For the risk analysis of dispenser gas leakage, this event was set as evidence to estimate the posterior probability of the basic events. Results are shown in Table 6.

Table 6 shows the probabilities of the intermediate events, the top event, and the consequences of its occurrence using BT and BN methods (the probability calculated for basic events is the same in both BT and BN methods).

Table 6. Results of BT and BN probabilities
Tabela 6. Wyniki prawdopodobieństwa dla metod BT i BN

Top event, intermediate event, and consequences	Prior probabilities (BT)	Posterior probabilities (BN)	Updated probability (BN)
Top Event	9.45×10^{-2}	8.89×10^{-2}	1
IE01	1.96×10^{-2}	1.73×10^{-2}	1.95×10^{-1}
IE02	2.53×10^{-2}	2.22×10^{-2}	2.50×10^{-1}
IE03	1.97×10^{-2}	1.93×10^{-2}	2.17×10^{-1}
IE04	2.03×10^{-2}	1.97×10^{-2}	2.22×10^{-1}
IE05	1.94×10^{-2}	1.90×10^{-4}	2.14×10^{-1}
IE06	9.36×10^{-4}	9.36×10^{-4}	1.05×10^{-4}
IE07	1.37×10^{-2}	1.32×10^{-2}	1.49×10^{-1}
IE08	5.55×10^{-3}	5.55×10^{-3}	6.25×10^{-2}
IE09	1.96×10^{-2}	1.92×10^{-2}	2.16×10^{-1}
IE10	1.97×10^{-2}	1.90×10^{-2}	2.13×10^{-1}
IE11	8.73×10^{-3}	8.51×10^{-3}	9.57×10^{-2}
IE12	1.05×10^{-2}	1.05×10^{-2}	1.19×10^{-1}
IE13	5.58×10^{-3}	5.58×10^{-3}	6.28×10^{-2}
IE14	1.17×10^{-4}	1.17×10^{-4}	1.31×10^{-3}
IE15	2.79×10^{-3}	2.79×10^{-3}	3.14×10^{-2}

cont. Table 6/ cd. Tabela 6

Top event, intermediate event, and consequences	Prior probabilities (BT)	Posterior probabilities (BN)	Updated probability (BN)
IE16	1.70×10^{-2}	1.70×10^{-2}	1.91×10^{-1}
IE17	3.96×10^{-3}	3.96×10^{-3}	4.46×10^{-2}
C1	9.45×10^{-3}	8.89×10^{-3}	1.00×10^{-1}
C2	3.36×10^{-3}	3.16×10^{-3}	3.56×10^{-2}
C3	2.02×10^{-3}	1.90×10^{-3}	2.13×10^{-2}
C4	3.03×10^{-3}	2.85×10^{-3}	3.20×10^{-2}
C5	7.85×10^{-3}	7.39×10^{-3}	8.31×10^{-2}
C6	4.71×10^{-3}	4.43×10^{-3}	4.98×10^{-2}
C7	7.07×10^{-3}	6.65×10^{-3}	7.48×10^{-2}
C8	2.27×10^{-2}	2.14×10^{-2}	2.41×10^{-1}
C9	1.36×10^{-2}	1.28×10^{-2}	1.44×10^{-1}
C10	2.05×10^{-2}	1.93×10^{-2}	2.17×10^{-1}

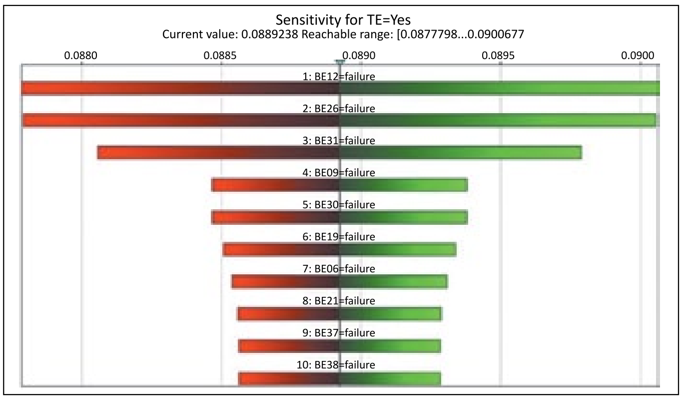

Figure 6. Tornado Diagram showing the top 10 critical basic events for dispenser gas leakage

Rysunek 6. Wykres tornado przedstawiający 10 najważniejszych głównych zdarzeń związanych z wyciekiem gazu z dystrybutora

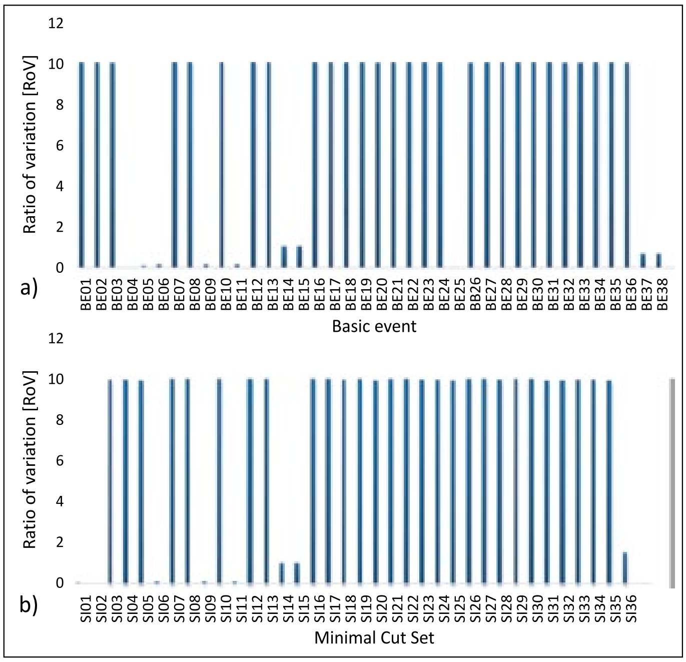

Figure 7. *RoV* of the basic events probabilities (a); *RoV* for MCSs probabilities (b)

Rysunek 7. Współczynnik zmienności prawdopodobieństw głównych zdarzeń (a); Współczynnik zmienności prawdopodobieństw minimalnych zbiorów cięć (b)

Sensitivity analysis

The sensitivity analysis was performed by two methods: 1) GeNIe2.1 software modelling and 2) Ratio of variation (*RoV*) approach.

1. The GeNIe software approach is direct, more comprehensive, and easy to use. Sensitivity analysis in GeNIe is performed by setting a node as the target node over which the GeNIe performs the sensitivity analysis.
   The sensitivity study was performed by setting the dispenser gas leakage (top event) as the target node, with the software performing a complete set of derivatives of posterior probability distributions over the target nodes using each of the probability parameters in the BN. Sensitivity rankings are shown in Figure 6. Based on the results (see Tornado Diagram), BE12 (cracking and corrosion of the dispenser hose) is ranked as the most sensitive or critical basic event.
2. The ratio of variation approach uses the models, the rate of variation of basic event, and MCSs to investigate the most critical basic event and MSCs contributors for dispenser gas leakage.
   In this study, the MCSs contributing to the dispenser gas leakage were ranked based on their criticality using *RoV*. As seen in Figure 7(b), the critical basic events shown in Figure 7(a) constitute the most critical MCSs in Figure 7(b).

Discussion

Among accident risk analysis methods, the BT model has proven to be efficient and reliable (Abimbola et al., 2014). This model is widely used in various fields of safety and risk analysis, including process safety, accident risk assessment, risk management, and the implementation of safety barriers (Khan and Abbasi, 1998; Lauridsen et al., 2002). According to the results of this model implementation, in the studied scenario, 38 basic events and 17 intermediate events resulting in dispenser gas leakage were identified.

In this study, immediate and delayed ignition prevention systems, Manual Emergency Shutdown Valve, Ball Valve, and the presence of compression and congestion of flammable and explosive materials were identified as safety barriers against dispenser gas leakage.

Although BT is one of the best and most popular methods in risk analysis, it has serious limitations and cannot be used in the dynamic risk analysis (Khakzad et al., 2013). Therefore, by mapping BT into a BN (Figure 5), these limitations were addressed.

Table 6 shows the results of deductive reasoning to predict the probability of scenario occurrence and its consequences using both BT (second column) and BN (third column). As seen, the occurrence probability of the top event by BN is equal to 8.89×10^{-2}, which is lower than the BT probability of 9.45×10^{-2}. It is noteworthy that all probability values calculated using BN slightly differ from those of BT due to BN's ability to consider conditional dependencies among basic events, which BT cannot (Khakzad et al., 2011). This consideration is significant in dependencies between IE02 and IE08 due to BE09 and BE10, and between IE05 and IE14 due to BE26 (see Figure 5).

Probability updating is one of the main applications of BN, where new information, or evidence, such as the observation of an accident and its consequences, reduces uncertainty and enables real-time and up-to-date accident scenario analysis. In probability updating, evidence propagates backward to the root nodes in the BN to update their prior probabilities based on Bayes' inference theorem (abductive reasoning) (Yang et al., 2017, Zarei et al., 2017a).

In this study, the top event (dispenser gas leakage) was assumed as the evidence, and the prior probabilities of all basic events, intermediate events, and consequence were updated. Table 6 shows the posterior probabilities of all intermediate events related to dispenser gas leakage occurrence for the most critical basic event contributors and the potential consequences (the fourth column). In this case, the probability of cracking and corrosion of the dispenser hose (BE12) increased significantly from 1.24×10^{-2} to 1.36×10^{-1} ($RoV = 9.96$), identifying it as the most critical basic event contributors. Possible causes include exposure of the dispenser hose to light, heat, and cold, impacts from vehicles and individuals, and the unsuitable materials used in its manufacture

The most probable consequence was C8, with occurrence probability of 0.241, primarily due to the effective operation of the emergency shutdown valve in controlling the release of CNG when the dispenser system fails. The results indicate that, in CNG stations, safety barriers can considerably mitigate the consequences of accident scenarios.

Comparing Figures 6 and 7, it is clear that relying solely on prior or posterior probabilities to identify critical events can lead to incorrect results, consistent with findings by Zarei et al. (2017b). Therefore, when implementing risk mitigation plans to reduce dispenser gas leakage failure probability, priority should be given to the most critical MCSs identified.

Conclusion

This study demonstrated the application of Bayesian network in comprehensive and dynamic safety risk modeling of CNG stations, enabling a risk-based investigation to identify the risk level of all hazards in CNG stations. Accordingly, dispense gas leakage was identified as the high-risk hazard in the CNG station. The accident scenario modeling was performed using a BT diagram for cause-consequence accident modeling, which was then mapped to a BN to capture dependencies and enable probability updating. Sensitivity analysis, conducted using GeNIe2.1 software modelling and the *RoV* approach, identified the most critical basic events and MCSs leading to accidents. The results confirmed dispenser gas leakage as the worst-case accident scenario, with cracking and corrosion in the dispenser hose as the most critical basic event contributing to the dispenser gas leakage. Among potential consequences, minor release was identified as the most probable consequence. The results of the study showed that identification of critical basic events should be carried out based on the ratio of variation in probabilities rather than solely on prior or posterior probabilities.

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