PRESENTING THE SOCIETAL RISK OF PIPELINES TRANSPORTING HAZARDOUS MATERIALS

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A Quantitative Risk Assessment (QRA) for systems dealing with hazardous materials is a well-established method in process industry to quantify and assess the risks on individuals and the society. For both the Individual and the Societal Risk, risk criteria exist depending on governmental or company-related regulations. The Individual Risk can be calculated here as the chance of fatality of one individual staying 24 h/day outdoor without protecting clothes at a certain location on-site or adjacent to the establishment. While Individual Risk results are usually presented in risk contours showing the acceptable and tolerable risk limit, Societal Risk results are often shown in an FN-curve approach. An FN-curve shows the cumulative frequency F of all system-related hazardous events that result in N or more fatalities. Regarding the Societal Risk of cross-country pipelines, the limiting frequency for the occurrence of an event with N fatalities has to be related to the pipe length. However, the failure frequency and the consequences of hazardous events and subsequently the Societal Risk vary along the alignment of a pipeline. Using an overall FN-curve approach for the presentation of the Societal Risk of a cross-country pipeline has a major shortcoming: The locations of the events with the highest contributions to the Societal Risk cannot easily be determined, which makes the application of risk mitigation measures difficult. Therefore, a different presentation method for the Societal Risk of gas pipelines is presented, which shows the Linear Risk Integral (LRI) over the pipeline alignment related to its length. The LRI can be interpreted as the cumulative risk for persons involved, i.e. sum of Individual Risks caused by the pipeline at the related location.

KEYWORDS: Pipelines, Quantitative Risk Assessment, Societal Risk

INTRODUCTION

Cross-country pipelines are the safest and most economic way for onshore transmission of hazardous gases and liquids. The majority of operating pipelines are handling crude oil, refined oil products or natural gas. However, the application of pipeline systems transporting other materials like LPG, ethanol, ethylene, hydrogen or ammonia is a common practice in industry. Additionally, recent research by *McCoy 2008*, *Det Norske Veritas (DNV) 2010* and *Kaufmann 2011* show that the use of CO_2 pipeline systems is of increasing interest as an element in the CCS (Carbon Capture and Storage) chain. The development of the pipeline technology is driven by meeting new technical challenges, by increasing cost efficiency and by mitigating the environmental and societal impact during construction and operation (*Feizlmayr 2011*). The latter aspect is getting more and more important in order to improve the image and the public acceptance of pipeline systems.

Regarding the pipeline transport of hazardous materials, a loss of containment (LOC) may lead to several hazardous scenarios affecting adjacent population and the environment. Depending on the material properties, explosions, fireballs, jet fires, pool fires or toxic contamination may occur. The *CONCAWE Report 2011* and the *EGIG Report 2011* show that the number of accidental incidents at oil and gas pipelines in Europe is decreasing consistently over the last decades which bears witness to the industry's improved control of pipeline integrity. However, incidents like the Ghislenghien gas explosion in 2004 (*ARIA 2009*) indicate that understanding, managing and mitigating risks is still of superior importance during the design, construction, commissioning and operational stages of a pipeline system, in order to ensure a safe operation.

For the investigation of risks in process industry several techniques like a Risk Based Inspection (RBI) or traditional risk analysis and risk assessments exist (*API 2000*). They can be performed according to a qualitative, quantitative or semi-quantitative approach. Their results are often used to apply risk mitigation measures during early design stages of process projects. Regarding quantitative approaches, a QRA is able to deliver results with a high level of detail and accuracy. QRA has been used since the late 1960s and has grown from a coarse tool to a precise tool demonstrating cost effective risk acceptability and risk minimization (*Nalpanis 2011*). Several guidelines (e.g. *de Haag 2005*, *RIVM 2009*) and commercial software like DNVs Phast Risk and TNOs RISKCURVES exist for the general performance of a QRA for process facilities. However, carrying out a QRA for cross-country pipeline systems requires special considerations during all study stages. In *BSI 2009* a guide to the application of pipeline risk assessment is given. Recently, *Spoelstra 2011* presented a method for the QRA of underground pipelines transporting hazardous substances. *Neunert 2011* recommends special considerations related to the QRA of gas transmission pipelines.

For the quantification and the assessment of the risks on individuals and the society, a QRA delivers the Individual and the Societal Risk results. For both, risk criteria exist depending on governmental or company-related regulations. The Individual Risk results are usually mapped in risk contours around the investigated facility or presented in form of a risk transect. Their probability values show the chance of fatality of one individual staying 24 h/day outdoor without protecting clothes at a certain location on-site or adjacent to the establishment. The Individual Risk can be assessed against risk criteria showing the acceptable and tolerable risk limits. The Societal Risk results are predominantly shown in an FN-curve approach. An FN-curve shows the cumulative frequency F of all system-related hazardous events that result in N or more fatalities.

Using the FN-curve approach for a pipeline system provides certainly valuable information on the overall Societal Risk emanating from this system. However, this method has also the major shortcoming that it cannot reflect the variation of the Societal Risk along the alignment of the pipeline due to variations of failure frequency, severity of consequences and density/distance of population along the pipeline. This would make it difficult to identify the locations with the highest contribution to the overall Societal Risk and to apply related selected effective mitigation measures to reduce this overall Societal Risk to a level which may be as low as reasonably practicable (ALARP). In order to close this gap, the present paper discusses the conventional FN-curve approach and a different risk presentation method which is based on calculating the Linear Risk Integral (LRI) as a function of pipe length.

QRA METHODOLOGY

Regarding the society, the general goal of a QRA is to quantify the Individual and Societal Risks related to a given facility and assess them against risk criteria in order to satisfy regulatory requirements. In order to ensure that the overall risk is acceptable or tolerable, risk mitigating measures are applied by following the ALARP principle (as low as reasonably practicable). Since risk is the product of likelihood and consequences of an undesirable event, it can be quantified by knowing the outcome of the event (number of fatalities) and its frequency of occurrence per year. Summing up the risk numbers of all hazardous events related to the investigated facility leads to the overall Individual and Societal Risk values.

In its elemental form, a QRA is comprised of five phases:

a. System definition
b. Hazard identification
c. Consequence analysis
d. Frequency analysis
e. Risk assessment

The consequence analysis and the frequency analysis can be performed in parallel. In the following the phases of a QRA are explained roughly focusing on special considerations for their application on pipeline systems transporting hazardous materials.

System definition

During the system definition phase, the goals and objectives are clarified and the boundaries of the investigated system are defined, considering the physical and operating limits. Regarding a pipeline, the physical system is usually a pipe section or a complete pipeline system. However, investigating only a discrete section of a pipeline system, one has to consider that a significant amount of inventory which is expelled due to a LOC scenario may additionally propagate from outside of the defined physical boundary limits.

Additionally, a complete site specific data collection is performed during the system definition phase including information on weather, material properties, population, pipeline operation, potential ignition sources and on existing risk mitigation measures. Since all this data may vary along a given pipe alignment, the data collection for conducting a QRA can be very time consuming. Additionally, information about soil cover depth, soil quality, coating conditions and laying procedures has to be included for buried pipelines.

Hazard identification

In order to identify all system related hazardous scenarios several techniques like a Hazard and Operability Study (HAZOP), a Failure Mode and Effects Analysis (FMEA), checklist approaches or a Fault-Tree Analysis (FTA) are available. For cross-country pipelines the hazardous events are LOC scenarios leading to the release of hazardous material followed by potential fire, explosion or contamination events. As proposed in *BSI 2009* and by *Spoelstra 2011*, a QRA for transmission pipelines should cover a full bore rupture and typical leak scenarios depending on the incident causes and the pipe diameter. A LOC scenario occurring at a pipeline may occur due to different causes. However, depending on the amount and type of release (continuous, instantaneous) and the material properties, different hazardous events may occur.

Since a LOC can appear at any position along the pipe alignment, the calculation of the events is related to discrete locations. Proper discretization plays an important role, as it affects calculation effort and accuracy. According to *Jo 2005*, the discrete pipe sections should be short enough not to influence the calculated results. A value of 10 m applied for the length of the discrete pipe sections is proposed in the regulatory standards for performing risk analysis of transmission gas pipelines in Switzerland (*Swissgas 2010*).

Consequence analysis

For each identified hazardous scenario, a chain of subsequent consequences is modelled starting from the release of hazardous material and ending up in the determination of quantified values describing the hazardous effects on the population (number of fatalities). The logical path to the possible end events can be considered based on an event-tree analysis. The results depend on the amount and the physical properties of the material, on its toxicity and flammability, on the leak size and the release conditions (rate, duration and direction) as well as on the weather and wind conditions. After defining the relevant properties of a LOC scenario, the calculation of the discharge and dispersion behaviour of the released substance is performed.

For pressurized below ground pipelines, the release is often accompanied by a crater formation yielding the discharged material in vertical direction. The hazardous effects of toxic or contaminating and persistent materials can be directly quantified from the dispersion calculation results combined with the exposure duration. Considering flammable materials, the effects of heat radiation or overpressures are determined by calculating the fire or explosion events, respectively. Therefore, the presence of oxygen (air) and ignition sources are required. Regarding cross-country pipelines aligned in rural areas, explosive events creating overpressures are hardly expected to occur, since an explosive pressure build up needs a flammable substance-air mixture trapped in a confined environment. However, the Ghislenghien gas explosion (*ARIA 2009*) showed that explosions scenarios have to be considered in a pipeline risk assessment. Possible heat radiation effects are due to flash fires, fireballs, jet fires or pool fires.

Frequency analysis

A frequency and probability analysis is performed in order to quantify the Individual and Societal Risks within a QRA. This includes the frequency of occurrence of all identified hazardous scenarios, the probabilities of different weather scenarios, the immediate and delayed ignition probabilities and the probability of presence of population located indoor and outdoor at the affected area. For more frequent major failure causes like external interference, construction defect, material failure, corrosion, ground movement, hot-tap made by error or other/unknown, historical data is used to define the appropriate frequencies and probabilities. For cross-country oil and gas pipelines appropriate numbers can be found in the regularly updated *CONCAWE Report 2011* and *EGIG Report 2011*, respectively.

Risk assessment

Combining the results of the consequence analysis with the frequency and probability data leads to the risk results for all investigated hazardous scenarios of a given system. Regarding the risk on the population, a QRA provides Individual and Societal Risk results. The quantified Individual Risk results are generated out of a risk summation approach by summing up the probabilities of fatality due to all identified hazardous events to a location-specific probability of fatality. Performing these calculations for a complete area, results in the Individual Risk contours.

The Societal Risk results measure the risk to a number of people located in the effect zones of the incidents. It generally shows the frequency distribution of multiple fatality events. As mentioned above the Societal Risk is usually presented in forms of FN-curves showing the frequency F of all events leading to N or more fatalities. For both the Individual and the Societal Risk, risk criteria exist in order to asses their acceptability and tolerability. Following the ALARP principle, appropriate risk mitigation measures may be applied in early project stages to ensure a safe operation. Regarding cross-country pipelines such mitigation measures have to be applied at special locations which shall be identified by analysing the Individual and Societal Risk results. However, using FN-curves to identify the locations of the hazardous events with the highest contribution to the Societal Risk is often difficult. Different analysing and presentation methods for the Societal Risk of cross-country pipelines transporting hazardous materials are presented in the following.

PRESENTING SOCIETAL RISK

The most common way of presenting Societal Risk is generating FN-curves. An FN-curve shows the cumulative frequency F of all events leading to N or more fatalities related to an investigated process facility. Figure 1 shows a typical FN-curve for a given establishment and the appropriate Societal Risk criteria in the UK and the Netherlands according to *CCPS 2009*.

Figure 1 indicates that the assessment of Societal Risk against given risk criteria can be easily performed using the FN-curve approach. Depending on the regulative requirements the Societal Risk can be ‘acceptable’, ‘intolerable’ or ‘tolerable but not acceptable’. In the latter case, risk mitigation has to be performed according to the ALARP principle, i.e. the risk is only tolerable if risk reduction is impracticable or its costs are in disproportion to the gained improvement. Some risk criteria may not include an ALARP zone.

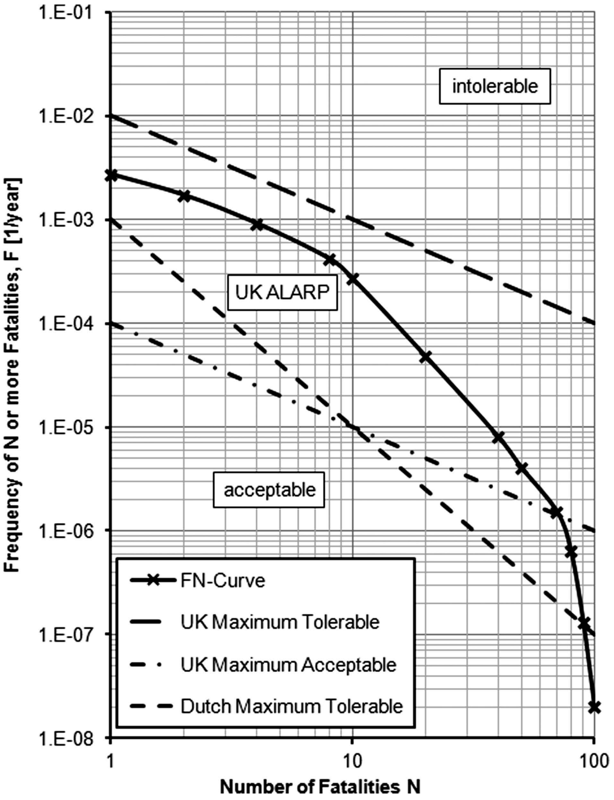

Figure 1. Typical FN-curve and UK/Dutch Societal Risk criteria for a process facility

In order to enable a comparison between different facilities the Societal Risk can be reduced to a single number known as the Societal Risk Index (SRI) or Potential Loss of Life (PLL). According to *API 2000*, this index is generated by multiplying the frequencies of occurrence F with their corresponding numbers of fatalities N of each single event and summing up these numbers for all events related to the investigated facility.

Regarding the presentation of the Societal Risk of pipeline systems, a shortcoming of the traditional FN-curve approach is obvious. Since an FN-curve shows the Societal Risk of all events related to a facility, comparability between different pipelines or pipeline routes with different lengths is not applicable. However, several proposed methods exist in literature with appropriate length-related risk criteria. According to *Spoelstra 2011*, the Societal Risk of pipelines in the Netherlands is assessed per 1 km pipe length. The tolerability frequency limit F_{lim} of 1 km pipeline for the occurrence of an event resulting in N or more fatalities is given in Eq. (1).

$$F_{\text{lim}} = \frac{10^{-2}}{N^2} \tag{1}$$

Similar regulations exist in the UK. According to *BSI 2009*, the acceptability limit for the Societal Risk of any 1 km section of a pipeline route is defined by Eq. (2) separating the acceptable area from the ALARP area. However, since the UK risk criteria are not covering a tolerability limit, a comparison with the Dutch risk criteria presented in Eq. (1) is not straight forward.

$$F_{\text{lim}} = \frac{10^{-4}}{N} \tag{2}$$

Figure 2 shows the resulting frequency limits of Eqs. (1) and (2) in an FN diagram, corresponding to the Societal Risk criteria of 1 km pipeline in the Netherlands and UK, respectively.

Additionally, *BSI 2009* proposes to generate a site-specific FN-curve by factoring the frequency values F by a factor of 1 km divided by the investigated pipe length and to assess the resulting Societal Risk against the criteria given in Eq. (2).

A different approach to assess the Societal Risk of gas transmission pipelines is recommended in Switzerland. According to *Swissgas 2010*, the highest number of fatalities of the possible events occurring along the pipeline route is determined for each 10 m section of pipe. If the worst case consequences exceed a number of 10 fatalities at a given location, an FN-curve is generated for a pipeline segment of 100 m at this position. The FN-curves of each investigated 100 m pipe segment are assessed against risk criteria presented in Figure 3.

Although the above mentioned approaches result in FN-curves related to a specific length allowing a comparison between different pipeline systems or pipeline routes, they still have three major shortcomings which are described in the following:

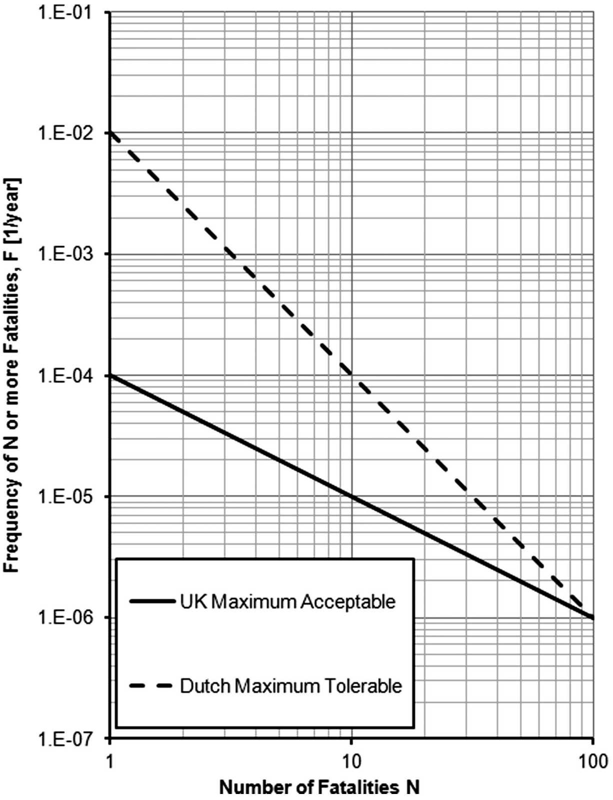

Figure 2. UK/Dutch Societal Risk criteria for 1 km of pipeline

a. All above mentioned approaches to assess the Societal Risk are based on a section-wise determination of the FN-curves and comparison of them against risk criteria. However, the segmentation and selection of the investigated pipeline route sections is not defined in the regulatory regarding the exact position of the section's boundaries, although this may have a significant impact on the Societal Risk results. One considers for example a high pressurized gas pipeline aligned over several km through a rural region in the UK with a low population density including 1 km aligned adjacent to a highly populated area. Generating the FN-curve for the 1 km pipe section near the highly populated area, may result in potential high Societal Risk values located in the ALARP zone due to high consequences (number of fatalities). In comparison, choosing the pipe sections boundaries in the middle and 500 m up- and downstream of the highly populated area, leads to two pipe sections whose FN-curves will possibly be located in the acceptable zone showing lower Societal Risk results for each pipe section.
b. As consequences and failure frequencies of hazardous events usually vary along a given pipeline route, significant differences of the Individual and Societal Risks over length exist. Thus, for an efficient application of

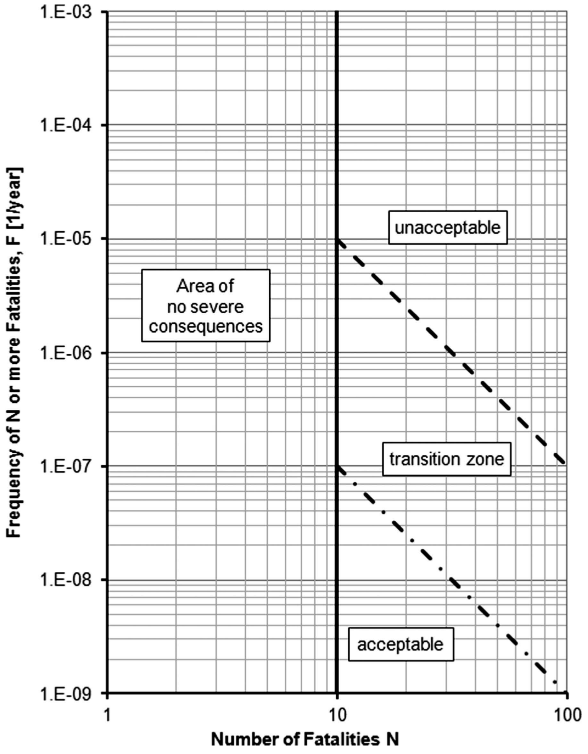

Figure 3. Societal Risk criteria in Switzerland, Swissgas 2010

risk mitigation measures, a precise detection of the pipe sections which are mainly contributing to the risks is required. Depending on the failure causes and the development of related hazardous scenarios, risk mitigation is recommended — e.g. re-routing, relocation of occupied zones, increased soil cover, increased pipe wall thickness, mechanical protection, visual signs (e.g. marker posts, warning tape), change in operational conditions, etc. Regarding long cross-country pipelines, the results and conclusions of a site-specific FN-curve are often insufficient for the application of adequate risk mitigation measures. Further, for identifying the exact positions where to apply mitigating measures, even sectional FN-curves related to 1 km or 100 m pipeline length are often not suitable.

c. Concerning the performance and the reporting of risk assessments related to long cross-country pipelines, the presentation of the Societal Risk results requires the calculation and presentation of numerous FN-curves. This may often result to a loss of track during the study and documentation overload. Considering a pipeline system of 100 km length, the generation of 100 FN-curves is required in the UK and the Netherlands. In Switzerland a number of up to 1000 FN-curves may be required for the same pipeline.

An alternative approach to present the Societal Risk of linear systems is addressing the Societal Risk results along the length of the pipe route. *Henselwood 2006* calculated a risk score of a pipeline and measured the risk as a function of location. In his studies, the risk score is composed of a combination of individual, societal, financial, environmental and regulatory risks.

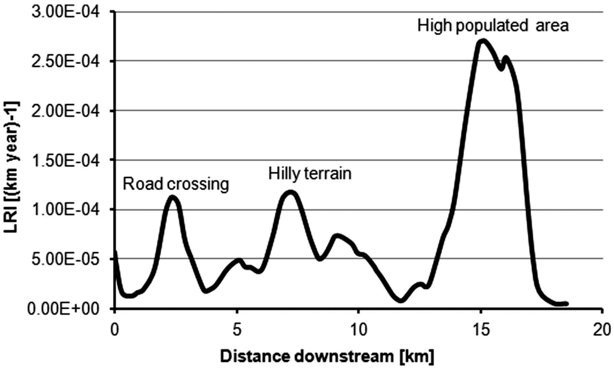

Figure 4. Societal Risk of a pipeline: LRI curve over pipe distance

For the presentation and investigation of the Societal Risk related to cross-country pipelines transporting hazardous materials, we recommend calculating the location-related Linear Risk Integral (LRI) over the pipe length. The LRI can be interpreted as the Societal Risk Index (SRI or Potential Loss of Life, PLL) of a linear segment with a discrete length Δl. The LRI of a pipeline segment is calculated of the frequencies F and corresponding number of fatalities N of n contributing events related to the discrete segment length Δl. For a pipe segment located at a distance x the LRI can be determined with Eq. (3).

$$LRI(x) = \sum_{i}^{n} \frac{F_i(x) \cdot N_i(x)}{\Delta l} \qquad (3)$$

The LRI is a measure of the Societal Risk per km and year and can be interpreted as the cumulative frequency of fatalities per year caused by 1 km of pipeline at the related location. An example is shown in Figure 4. Figure 4 presents the LRI curve over pipe distance of a given pipeline with a length of 18.5 km.

The curve in Figure 4 clearly indicates the location of pipe sections with a significant contribution to the Societal Risk. At a road crossing near km 2.5 the pipeline is prone to external impacts due to car and truck accidents. Here the Societal Risk is high due to increased failure frequencies. At km 7 the pipe is aligned through hilly terrain where an increased probability of ground movement events (land slides) leads to a high Societal Risk. For hazardous events occurring at the pipeline near km 15 an increased number of fatalities and therefore higher consequences are expected due to the vicinity of a high populated area.

From the results shown in Figure 4 it is obvious where to implement measures in order to achieve the most effective risk mitigation. Since the Societal Risk at a given location is composed of the frequency and consequences of several hazardous events which are based on several failure causes, a detailed investigation is required to select the best applicable mitigating measures. Therefore, generating an LRI curve over pipe length is an advantageous method for comparing different pipeline systems and routes, to provide an integrated overview of the pipe related Societal Risk and to apply risk mitigation measures in a highly efficient manner. However, since regulatory risk criteria corresponding to the presented 'LRI over pipe distance'-curve doesn't exist yet, the generation of section-wise FN-curves is additionally required for the conduct of a complete Societal Risk assessment in the frame of a QRA.

SUMMARY AND CONCLUSION

The present paper focuses on the presentation of the Societal Risk of pipeline systems transporting hazardous materials. In the scope of a Quantitative Risk Assessment (QRA) a frequency and consequence analysis of identified hazardous scenarios leads to the quantified Societal Risk values. Risk criteria exist for the assessment of the Societal Risk values based on the FN-curve approach related to discrete pipeline sections. Concerning the comparability of different pipeline systems and the application of risk mitigation measures, calculating and generating FN-curves is not very efficient. An alternative approach is presented based on a location specific determination of the Societal Risk along the pipe alignment by calculating the Linear Risk Integral (LRI). Presenting an LRI curve over pipe distance leads to a precise identification of the pipeline sections with the highest contribution to the Societal Risk. This allows a highly efficient implementation of potential risk mitigation measures.

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