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A THEORETICAL APPROACH OF A NEW INDEX-BASED METHODOLOGY FOR RISK ASSESSMENT OF PIPELINES (I)

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Abstract

Environmental and territorial compatibility of industrial activities can be evaluated by considering several criteria, usually formalized in the contest of a Strategic Environmental Assessment (SEA); the pipelines sector, however, is not as well standardized as others. In this paper, a new methodology to evaluate territorial compatibility of proposed pipelines is presented. This approach can be useful to assess proper development compatibility of oil and gas pipeline networks, and it could represent an example of specific technical guidelines supporting territorial planning and management. The evaluation criteria in the proposed method are both qualitative and quantitative, and are consistent with those used for similar fixed installations (e.g. LNG storage). The methodology uses a specific checklist in order to calculate a relative pipeline risk index. The checklist and risk index are thus easyly determined and compared when different technical solutions are examined, in order to rank them accordingly to their environmental compatibility and safety aspects.

Key words: environmental compatibility, pipelines, risk index, territorial planning

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1. Introduction

The construction of pipelines or pipeline networks must satisfy a well-defined set of regulations, and must be implemented according to stringent technical guidelines. Nevertheless, there are no generally applicable and coherent, guidelines to evaluate such an infrastructural impact on the surrounding natural environment (the so called "environmental compatibility") and the associated risk (to both environment and human health) induced by their presence; and in particular, when these pipelines are meant for the conveyance of dangerous fluids (such as liquid or gaseous hydrocarbons) and they are located in critical areas (Kalatpoor et al., 2011; Di Mauro et al., 2012).

The evaluation of environmental aspects and risks related to the implementation and operation of the pipelines is a mandatory step for good planning (Zhou and Liu, 2012; Han and Weng, 2011); however, in this field, evaluations are sometimes incomplete (O'Connell and Hurley, 2009).

Attempts to establish objective criteria to assess environmental implications and risks associated with the presence of large pipeline networks have been also worked out (Van Hinte et al., 2007; Jo and Crowl, 2008); in many Countries, as well as in Italy, studies to develop tools for monitoring and managing the transport of gaseous and liquid substances, either through pipelines or other systems have been carried out (Torretta, 2009; Torretta et al., 2007, 2012).

As far as environmental compatibility, pipeline projects must undergo an Environmental Impact Assessment (EIA) procedure if their dimensional characteristics (overall length and/or diameter) so require. For example, in Italy relevant regulations are given by Public Law 152/2006, deriving from the transposition of previous EU Directives, including EC Directive, (2001), EEC

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Directive, (1985), as modified by EC Directive, (1997), and EC Diective, (2003): according to the above, gas, oil and chemical products pipelines are subject to EIA if their diameter is more than 800 mm, and their length over 40 km. Preliminary screening for the possible application of the EIA procedure is required for projects of smaller sizes (from 400 mm and 20 km, respectively). Within the EIA procedure, alternative technical solutions could also be examined, assessing not only technological and construction issues, but also the optimal territorial layout of the pipeline. The latter could also be examined within a SEA procedure, if so required (Torretta and Ionescu, 2012).

In either case, a comparative evaluation of alternate pipeline configurations (e.g. layout, technical solutions) is of critical importance in the entire technical/administrative process represented by the SEA/EIA procedures, and can be carried out using different discriminating criteria, including those concerning overall minimization of environmental pressure under alternative options, cost optimization for both construction and operation, or minimization of risk induced onto the territorial surroundings, including environmental, biological and human health aspects.

In current practice, SEA/EIA procedures often do not appropriately address all those issues connected to territorial compatibility, and related to safety and risk induced onto human health and safety, but limit themselves to mere environmental-related considerations (the so-called "environmental compatibility"). For these reasons, the authors herein propose an index-based methodology for pipeline risk assessment which takes into account all the aforementioned issues.

The outcome of this methodology is synthetic (a numeric index); therefore, it is optimal to implement when considering possible design options (e.g. different layouts, technical solutions). In this case, the one obtaining the maximum index score is that that will also minimize both environmental and population-health impacts.

The proposed methodology can be useful to ensure a high degree of consistency and reliability for all risk management process components of a project, facilitating its continuous evaluation throughout its design life, and assisting in-course decision modifications, should any new information become available (Jardine et al., 2003). The paper describes the theoretical approach of the methodology, illustrating the elements composing the index and its application details.

2. Theoretical approach

Conveyance of products via pipelines implies a certain degree of risk due to the probability of the pipeline failure with following leakage and damage to surrounding areas. The consequent damage will be higher in sensitive areas, which can be defined as those that are highly populated, intensively infrastructured or ecologically sensitive (Great Britain Treasury, 2004).

Risk (R) can be assumed to be proportional to both the expected damage that may be caused by an event (M, defined as expected losses per accident) and the probability (P) of the occurrence of such an event (Muhlbauer, 2006) (Eq. 1):

$$R = M \times P \tag{1}$$

Thus, the Pipeline Risk Index (PRI) can be calculated as (Eq. 2):

$$PRI = ECI \times FPI \tag{2}$$

where: ECI is the Event Consequences Index, connected to the accidental consequences of the expected damage (M), and FPI is the Failure Probability Index, connected to pipeline failure probability (P). Both terms of (2) are illustrated below in detail.

2.1. Failure Probability Index

The Failure Probability Index (FPI, with possible value ranging between 0 and 1, by definition) is here defined by the following expression (Eq. 3):

$$FPI = 1 - \prod_{l=1}^{4} FSPI_l / 100 \tag{3}$$

where $FSPI_l$ is the Pipeline Survival Probability Index (ranging between 0 and 100) referred to any potential failure caused by each of the following main possible causes (Gagliardi et al., 2007):

- corrosion (l=1);
- third-party damage (l=2), referring to any pipe accidental damage not related to pipeline management;
- improper operation (l=3), which considers the potential pipeline failure caused by errors committed when designing, building, operating or maintaining the pipeline;
- improper design (l=4), which considers the pipeline capability to withstand failure.

Each of these pipeline failure causes has been selected, catalogued and assessed according to various factors, properly weighted. Using an index model, numerical $FSPI_l$ values ranging from 0 to 100 are then assigned to the relevant conditions and activities of the pipeline system (Hicks and Ward, 2004).

These values may represent both risk-reducing and risk-increasing conditions, with different individual weights corresponding to the importance of the single item in the risk assessment process. Actual scoring adopted is based on published statistics (when available) or, when data were unavailable, on assessments made by experts (Muhlbauer, 2006): a multidisciplinary panel composed by a geologist, a pipeline construction and an environmental safety engineer defined the score assignment methodology herein described, following the approaches of Hicks and Ward (2004) and Dey (2002). Specifically, data employed by the panel were selected on the basis of reported findings (Francis, 2002; McCallum and Illson, 2004; Muhlbauer, 2006).

Scores approaching or equal to 1 denote excellent safety conditions for the pipeline, while values close to zero indicate the existence of high risk conditions. The general formula for $FSPI_l$ calculation is (Eq. 4):

$$FSPI_l = \sum_i \sum_j \sum_k s_{lijk} \tag{4}$$

where $s_{l\,ijk}$ is the assigned score regarding issues (*i*), sub-issues (*j*) and sub-sub-issues (*j*) of each cause (*l*), as listed in Tables 1 through 4.

The corrosion probability index ($FSPI_1$) (Table 1) is assessed by taking into account the contribution of:

- atmospheric corrosion (*i*=1; weight: 10%), which considers the pipe exposure to the atmosphere and the atmosphere characteristics (sub-issues 1 and 2), such as the presence of chemicals, moisture and temperature (sub-sub-issues 1-5);
- internal corrosion (*i*=2; weight: 20%), which considers the characteristics of the conveyed product and the prevention measures undertaken for reducing the phenomenon;
- subsurface corrosion (*i*=3; weight: 70%), which considers soil corrosiveness, anaerobic microorganism activity, mechanical corrosion effects, cathode protection, and the presence of pipeline protective coating.

The third-party damage index ($FSPI_2$) can be assessed (Table 2) considering the:

- pipe cover characteristics (*i*=1; weight: 25%), especially the depth of cover, the cover material, the presence of casing, warning tape or concrete as reinforcing structure;
- presence of above-ground activities, facilities and/or public education programs which considers the pipeline presence (*i*=2; weight: 50%);
- awareness of the pipeline presence (*i*=3; weight: 20%) through signposting along the pipeline route;
- patrolling frequency and type (*i*=4; weight: 5%).

The incorrect operation index ($FSPI_3$) can be evaluated (Table 3) considering the following aspects (Kirkwood et al., 1994):

- design (*i*=1; weight: 30%), including hazard identification, material selection, existing safety systems, the potential Maximum Operating Pressure (MOP) and the eventual conditions of overpressure;
- construction (*i*=2; weight: 20%), related to the inspection, materials, handling and coating;
- operation (*i*=3; weight: 35%), depending on the presence of written procedures covering all of the aspects of pipeline operation, Supervisory Control And Data Acquisition (SCADA), safety programs and training;
- maintenance (*i*=4; weight: 15%), referring to an eventual lack of management attention to maintenance and any incorrect maintenance requirements or procedures.

Finally, the design index ($FSPI_4$) can be calculated (Table 4) by considering the:

- adopted safety factors (*i*=1; weight: 35%);
- fatigue (*i*=2; weight: 10%), which weakens the material through repeated cycles of stress and potential surge;
- integrity verification (*i*=3; weight: 10 %);
- probability of land movements (*i*=4; weight: 25%);
- probability of seismic phenomena (*i*=5; weight: 20%).

2.2. The Event Consequences Index (ECI)

The general expression proposed to determine the ECI, that is the expected damage which may be caused by a specific event (range: 0÷1) is given as (Muhlbauer, 2006) (Eq. 5):

$$ECI = PP \times D \times R \times V \tag{5}$$

where: *PP* is the potential product hazard (range: 0÷1); *D* represents dispersion and migration of pollutants through each environmental medium (range: 0÷1); *R* represents the receptor vulnerability (range: 0÷1); *V* is the leak volume (range: 0÷1); ECI represents the magnitude of the accident effects: it is a function of the characteristics of the product transported by the pipeline through its hazard index, *PP*, which assumes different values depending on the type ofpotential hazard: environmental toxicity, flammability, explosion, etc.

Assessment of the ECI values is carried out by considering the potential consequences caused by the pipeline failure, which can be divided in:

- environmental contamination (including soil, atmosphere, surface water and groundwater), with subsequent damage to flora, fauna, drinking water, human health (caused by the ingestion, inhalation, and skin absorption of hazardous substances transported by the pipeline and released by failure) etc.;
- mechanical effects: such as soil erosion, washout etc.;
- fire/ignition scenarios, such as fireballs caused by a boiling liquid expanding vapour explosion (BLEVE), quite unusual in pipelines, jet fires (engine exhaust), vapour cloud explosions, and pool fires, with the production of intense radiant heat.

Therefore, different specific forms for Eqs. (6-11) can be specified for each of the above as:

Table 1. Corrosion probability index ($FSPI_1$) scores

Issue (i)	***Sub-issue (j)***	***Sub-sub-issue (k)***	***Option***	***Score***
Atmospheric corrosion (1)	Atmospheric exposition (1)	Exposition to water (1)	$l_{exp\,\%}$: percentage length of exposition	$0.05\ l_{exp\,\%}$
		Casing pipe (2)	Presence	1
		Insulation on aboveground pipe or support/hangers (3)	Presence	2
	Atmosphere composition (2)	No chemical agents (4)	Low humidity and/or temperature	2
			High humidity and/or temperature	1.2
			High humidity and/or temperature in marine environment	2
			High salt concentrations and occasional submersion in marine environment	0.8
		Presence of chemical agents (5)	High humidity	0.5
			Marine environment	0
Internal corrosion (2)	Conveyed product characteristics (1)		Strongly corrosive (high incompatibility with pipe material)	0
			Mildly corrosive (slow pipe damage)	4
			Corrosive under special conditions (e.g. introduction of reactant chemical)	7
			Non-corrosive (no incompatibility)	10
	Prevention measures (2)		None	0
			Not needed	10
			Internal monitoring (e.g. on-line potential corrosion probe)	2
			Inhibitor injection (e.g. oxygen-scavenging chemicals, biocides)	4
			Internal coating (e.g. plastic, concrete)	5
			Intelligent pigging	3
			Operational measures to prevent impurities (e.g filter, dehydration systems).	3
Subsurface corrosion (3)	Soil characteristics (1)	Soil resistivity (1)	Low (high corrosiveness)	0
			Medium	3.5
			high (low corrosiveness)	7
			No information	0
		Anaerobic microorganism activity (2)		0-3
		$pH < 3$ or $pH > 9$ (3)		0-5
		HSCC[a] and SSCC[b] phenomena (4)		0-5
	Cathode protection (2)	Effectiveness (5)		0-15
		Presence of high voltage (>33 kV) alternate current (HV-AC) power lines (6)	No HV-AC power lines are within 300 m of the pipeline	2
			HV-AC power lines are within 300 m of the pipeline (with preventive measures)	1
			HV-AC power lines are within 300 m of the pipeline (no preventive measures)	0
		Shielding (7)		0-1
		Interference by other buried metals (8)		0-7
	Pipeline coating (3)	Appropriateness of the coating type (9)		0-5
		Coating application quality (10)		0-5
		Inspection and defect correction program quality (11)		0-15

[a] *Hydrogen Stress Corrosion Cracking.*
[b] *Sulfide Stress Corrosion Cracking.*

Table 2. Third-party damage index ($FSPI_2$) scores

Issue (i)	***Sub-issue (j)***	***Sub-sub-issue (k)***	***Option***	***Score***
Pipe cover (1)	Minimum depth of cover (1)	h: depth of cover (in m)	$h \leq 0.30$ m	0
			$h > 0.30$ m	$h/7.5$
	Cover material (2)		Sand	1
			Rock	1.5
	Concrete coating thickness(3)		0.05 m	2
			0.10 m	4
	Pipe casing (4)			8
	Concrete slab (reinforced) (5)			8
	Warning tape (6)			2
Above-ground activities (2)	Surface human or natural activity level (1)		High	0
			Medium	10
			Low	15
			None	20
	Facilities (2)		No facilities	15
			Facilities at a distance less than 100 m	0
			Facilities at a distance more than 100 m	6
	Facilities details (3) (if present)	Presence of nearby trees, walls or other substantial structures		4
		Warning and other signals		3
		Area surrounded by a fence		2
	Public education program (4)			0-15
Right-of-way condition (3)			Excellent (e.g. clear indication of the pipeline route, visible signs at all roads, railroads, ditches and water crossings)	20
			Medium (e.g. non-uniform indication of the pipeline route, lack of visible signs at roads, railroads, ditches and water crossings)	13
			Below medium (e.g. indistinguishable route, route overgrown by vegetation)	8
			Poor (e.g. pipeline route is indistinguishable)	0
Patrolling frequency (4)			None	5
			Internal monitoring (e.g. potential corrosion probes)	2
			Inhibitor injection (e.g. oxygen-scavenging chemicals, biocides)	0

Environmental pollution:

Soil:

$$M_{1,SS}=PP_1\, D_{1,Ss}\, R_{1,SS}\, V \qquad (6)$$

Surface water:

$$M_{1,WSup} = PP_1\, D_{1,W}\, R_{1,WSup}\, V \qquad (7)$$

Groundwater:

$$M_{1,WGr} = PP_1\, D_{1,W}\, R_{1,WGr}\, V \qquad (8)$$

Atmosphere:

$$M_{1,At} = PP_1\, D_{1,At}\, R_{1,At}\, V \qquad (9)$$

Mechanical effects:

$$M_2 = PP_2\, D_2\, R_2\, V \qquad (10)$$

where $D_2 = 1$

Fire/explosion scenario:

$$M_3 = PP_3\, D_3\, R_3\, V \qquad (11)$$

where $D_3 = 1$

In the above expressions, the dimensions of the impacted area are not considered (and in fact they can not be known *a priori*), however they are implicitly contained by the parameters concerning product characteristics, receptor presence and vulnerability, involved environmental sector, and quantity of the released product. These are analysed in some detail below.

2.2.1. Potential Product Hazard (PP)

Potential product hazard is analysed with respect to any potential scenario of possible environmental contamination, mechanical effects and fire/explosion (parameters PP_1, PP_2 and PP_3).

The first scenario (PP_1, value range: $0\div1$) is related to various effects of the product that can be released upon pipeline failure (toxic/heavily toxic, injurious to health, corrosive, irritating, carcinogenic, mutagenic, toxic to the human reproductive system, hazardous for the environment).

The second scenario (*PP_2*, value range: 0÷1) concerns hypothetical mechanical effects caused by any possible incidental event occurring along the pipeline. The third scenario (*PP_3*, value range: 0÷1), relates to explosive properties of the substance (ignitability, flammability and reactivity).

2.2.2. Dispersion (D)

Unintentional/accidental episodes of product release from a pipeline will impact a specific surrounding area, with an extension determined by the released product quantity and characteristics, site characteristics, accident topology etc.

Table 3. Incorrect operation index (*$FSPI_3$*) scores

Issue (i)	***Sub-issue (j)***	***Sub-sub-issue (k)***	***Option***	***Score***
Design aspects (1)	Hazard identification (1)	Documentation showing that complete hazard identification was performed	Presence	2
			Absence	0
	Safety control (2)		Reaching the inappropriate pressure operations is possible, no safety device is present	0
			Reaching the inappropriate pressure operations is possible, one safety protection level device	2
			Reaching the inappropriate pressure operations is possible, two or more safety protection levels	4
			Pressure remote monitoring (automatic overpressure protection is not present)	1
			Pressure remote monitoring. The controller can remotely prevent overpressure	2
			The MOP cannot be reached (a safety system is not necessary)	11
	Material selection (3)	Piping material information (e.g. operating and maintenance)	Available	2
			Not available	0
	MOP (4)		Normal operations could allow the system to reach the MOP (overpressure would occur fairly rapidly due to incompressible fluid or the rapid introduction of relatively high volumes of compressible fluids)	0
			Overpressure can occur due to a combination of procedural errors or omissions and the failure of the safety devices (at least two levels)	5
			Overpressure is theoretically possible (sufficient source pressure) but only through an extremely unlikely chain of events, including errors, omissions, and safety device failures at more than two levels of redundancy	10
			Pressure source cannot, under any conceivable chain of events, overpressure in the pipeline	15
Construction aspects (2)	Inspection (1)			12
				6
				0
	Verification of the material (2)			0
				2
	Joining (3)			0-2
	Handling (4)			0-2
	Coating (5)			0-2
Operational aspects (3)	Presence of written procedures covering all operations on pipeline (1)			0-10
	Presence of SCADA (2)			0-7
	Safety programs (3)			0-3
	Training (4)			0-15
Maintenance aspects (4)	Documentation			0-2
	Schedule			0-3
	Procedures			0-10

Table 4. Design index ($FSPI_4$) scores

Issue (i)	***Sub-issue (j)***	***Sub-sub-issue (k)***	***Option***	***Score***
Safety factor (1)	Ratio between the actual and theoretical pipeline wall thickness (t_a/t_{th} ;1)		$t_a/t_{th} \le 1$	-10
			$1.0 < t_a/t_{th} \le 1.1$	4
			$1.1 < t_a/t_{th} \le 1.2$	7
			$1.2 < t_a/t_{th} \le 1.4$	14
			$1.4 < t_a/t_{th} \le 1.6$	21
			$1.6 < t_a/t_{th} \le 1.8$	28
			$t_a/t_{th} > 1.8$	35
Fatigue and potential surge (2)	Fatigue (1)		High number of cycles[a]	0
			Low number of cycles[a]	7
	Potential surge (2)	*p*: pressure	$p \ge 1.1\ MOP$	0
			$p < 1.1\ MOP$	3
Integrity verification (3)	Pressure to Maximum Operating Pressure ratio (p/MOP; 3)		$p/MOP \le 1.10$	0
			$1.10 < p/MOP \le 1.25$	3
			$1.25 < p/MOP \le 1.40$	6
			$p/MOP > 1.40$	10
Land movements (4)			High: soil movements are common or can be quite severe	0
			Medium: soil movements are possible but rare or unlikely to affect the pipeline due to its depth or position	10
			Low: movements and damage are not likely. There are no recorded episodes of structural damage due to soil movements	18
			None: no evidence for any kind of potential problems due to soil movements	25
			No available data	0
Seismic activity (5)			Strong seismic activity	0
			Average seismic activity	10
			Low seismic activity	15
			None	20
			No available data	0

[a] *the threshold number of cycles between low and high depends both upon the pipeline material and the operative conditions (e.g. temperature, pressure)*

Released products can reach the atmosphere, surface water, soil, groundwater, and existing structures and infrastructure (buildings, sewers, roads, etc.); their potential transport must consider all environmental media and should consider degradation and reaction processes. In an index-based method, pollutant characteristics and soil/media properties can be used to define a lumped-parameter system able to describe the actual degree of pollution in each environmental medium following the release of a product. This gives information about both pollutant concentrations and dimensions of the impacted area.

The methodology used to attribute weight values dispersion sub-indexes *D* is the same one used for the determination of the *FPI*: an expert panel, starting from literature findings, attributed the values for the different cases:

- soil pollution ($D_{1,Ss}$). Soil pollution and any soil interaction with the pollutant can be evaluated by considering the product state and its possible degradation processes (biodegradation, photolysis, etc.,) with a ranking range of -0.2÷0. Surface water and groundwater pollution ($D_{1,Ac}$). Surface water and groundwater pollution deriving from interactions with the released pollutant can be evaluated by considering the product state and possible degradation processes, with a ranking range of -0.2 ÷0.
- atmospheric pollution ($D_{1,At}$). Atmospheric pollution effects and atmospheric interactions with the pollutant can be evaluated by considering the product state and possible degradation processes, with a ranking range of -0.2 ÷0.

Table 5 shows the weight values of the dispersion sub-indexes for different processes in the media considered.

The sub-index evaluation regarding $D_{1,Ss}$, $D_{1,Ac}$ and $D_{1,At}$ depends on many factors (e.g. the pipeline depth, product's water solubility, soil granulometry, organic matter content, partition coefficient and boiling point of released product, temperature, groundwater depth, soil porosity, saturation degree and atmospheric class of stability). More precisely, a range of variation has been attributed to sub-indexes: the actual value must be determined using a proportionality criterion as a function of such factors.

2.2.3. Receptor vulnerability (R)

The quantification of the vulnerability of the different possible receptors must consider two main relevant factors:

Table 5. Weight values of dispersion sub-indexes.

	GAS			***LIQUID***		
	Absorption	Dry/wet deposition	Solubilisation	Absorption	Solubilisation	Volatilization
$DD_{1,Ss}$	0÷0.35	0÷0.05	-0.1÷0	0÷1	-0.1÷0	-0.2÷0
$DD_{1,Ac}$	-0.1÷0-	0÷0.2	0÷0.03	-0.2÷0	0÷1	-0.2÷0
$DD_{1,At}$	-0.1÷0	-0.1÷0	-0.2÷0	-0.2÷0	-0.2÷0	0÷1

- The distance between the pipeline and the receptor (the migration pathway of the pollutants and the migration rate of the released product);
- The receptor topology, necessary to define the human exposure to the hazardous agents.

For the purposes of the proposed methodology, receptors are defined as geographically-referenced "objects" that may be exposed to the potential accident consequences. These "Objects" can be either of the following:

- Population (R_P; score: 0÷1), depending on land use and, in particular, population density (score: 0÷0.4), critical buildings (such as schools, hospitals, public markets and rehabilitation centres; points: 0÷0.4) and natural parks or areas with a high natural value (score: 0÷0.2) (Yo et al., 2008);
- Surface water (R_{WSup}; score: 0÷1), which is considered as a function of the number of water bodies that can be reached by the contamination, the existence of water bodies with a high natural value, water quality, etc.;
- Groundwater (R_{WGr}; score: 0÷1), depending on the groundwater depth, use and quality;
- Atmosphere (R_{At}; score: 1);
- Soil (R_{SS}; score: 1).

The vulnerability parameter values for the soil and the atmosphere have been established *a priori* as equal to 1, since these are environmental media that directly receive damage from a pipeline rupture. For water (whether surface or groundwater) the vulnerability parameter depends on the distance of the compartment from the rupture, the existing water quality levels and the specific use of the resource. Also effects on population can be considered indirect, and thus must be evaluated considering soil use and the presence of sensitive receptors (Sklavounos et al., 2006).

The empirical relationships used to calculate receptor vulnerability for each incidental event are shown below:

Environmental contamination (Eqs 12-17):

Soil

$$R_{1,SS} = 0.5\ R_P + 0.5\ R_{SS} \qquad (12)$$

Atmosphere

$$R_{1,At} = 0.5\ R_P + 0.5\ R_{At} \qquad (13)$$

Surface water

$$R_{1,WSup} = 0.5\ R_P + 0.5\ R_{WSup} \qquad (14)$$

Groundwater

$$R_{1,WGr} = 0.5\ R_P + 0.5\ R_{WGr} \qquad (15)$$

Mechanical effects:

$$R_2 = R_P \qquad (16)$$

Fire/explosion scenarios:

$$R_3 = R_P \qquad (17)$$

2.2.4. Released product volume (V)

In most cases, the extents of the consequences of a pipeline accidental release are related to the quantity of the released product. This depends on:

- the initial quantity released from the pipeline between the actual beginning of the failure event (t=0) and the time when an alarm is raised (score: 0÷0.4). This depends depending on the detection system adopted (i.e. online pressure monitoring, distance of monitoring points or offline monitoring) and its efficiency (score: 0÷2) and the product flow in the pipeline at the moment of the event (score: -0.2÷0);
- the quantity released from the time at which the alarm is raised to the time of cutting off the pipe breach (score: -0.3÷0). This is related to the promptness of the response and the efficiency with which the system is closed off (score: 0÷0.15), and again the flow in that moment (score: 0÷0.15);
- the residual product released after the pipe breach is solved (i.e. the breached sector is isolated; score: 0÷0.3) corresponding to the product present in the pipe volume between two closing automatic (or non- automatic) valves, and proportional to pipe diameter and length in the sector between the two consecutive valves.

2.2.5. ECI evaluation

The *ECI* describes the extent of damage caused by pipeline failure and product release (*M*). The ECI can be calculated by giving a specific weight to each M_i index described in Eqs. (5) The overall equation that can be used to define the *ECI* is therefore shown below.

$$\begin{aligned} M = {} & M_{1,SS}\ 0.4\ 0.25 + \text{(Soil pollution term)} \\ & + M_{1,WSup}\ 0.4\ 0.25 + \text{(Surface water pollution term)} \\ & + M_{1,WGr}\ 0.4\ 0.25 + \text{(Groundwater pollution term)} \\ & + M_{1,At}\ 0.4\ 0.25 + \text{(Atmospheric pollution term)} \\ & + M_2\ 0.2 + \text{(Mechanical effects term)} \\ & + M_3\ 0.4 \text{(Fire/explosion scenarios term)} \end{aligned} \qquad (7)$$

The maximum weighting coefficients (0.4) are applicable in the events of environmental contamination and fire/explosion scenarios. For standard cases, possible damages caused by mechanical effects have been assigned a weight of 0.2. Environmental contamination has been considered by applying the same weight coefficient (0.25) to the four environmental systems considered (air, soil, groundwater and surface water).

3. Conclusions

An index-based methodology has been proposed to assess a relative pipeline risk index determined as the product of the Failure Probability Index (*FPI*) and the Event Consequence Index (*ECI*). The methodology is considered to be applicable to the evaluation of pipeline design alternatives, taking into account the necessity of risk minimization, induced on the territorial surroundings, including environmental, biological and human health aspects.

The methodology herein described is index-based; therefore its response, being synthetic, is applicable when considering alternatives for different variants of one specific project (*e.g.* alternate routes). In this case, among different possible alternatives, the one that obtaining the best index score is the one that minimizes both environmental impact and population health impacts.

The weights and coefficients herein proposed are based on literature evidence, experts' knowledge, and estimates expressed by a multidisciplinary expert panel; however, they are not to be considered absolute, as the methodology result is not meaningful as an absolute value, but only as relative (comparative) ranking. Weights and coefficients values can therefore be modified for specific situations, as long as their proportions and relationships are not completely altered.

The methodology herein proposed would be best handled by means of an automated software application that is being currently developed. This software will be then applied on a case study in order to evaluate the methodology pros and cons, compared to conventional EIA criteria (Morris and Therivel, 2009).

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