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THE NEW PIPES CHOICE CRITERIA FOR WATER DISTRIBUTION SYSTEM

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EXTENDED ABSTRACT

Il corretto utilizzo della risorsa idrica è una componente essenziale dell'efficienza del funzionamento degli ecosistemi urbani, il cui equilibrio è legato alla ottimale distribuzione dell'acqua alle utenze. Lo sfruttamento intensivo delle risorse idriche rappresenta un elemento sensibile che determina la crisi della resilienza degli ecosistemi urbani. Gli impatti legati a una gestione sostenibile delle risorse idriche rivestono un peso crescente in dipendenza con i cambiamenti climatici, su piccola e larga scala (isole di calore urbano, buco dell'ozono), con l'inquinamento del suolo e con le dinamiche demografiche e i processi di urbanizzazione. A rendere complessa la transizione verso una gestione sostenibile delle risorse idriche è, certamente, la vetustà e l'inefficienza delle infrastrutture che non risultano adeguate agli attuali criteri di sostenibilità. La necessità di ricorrere a criteri di ottimizzazione delle reti idriche, che tengano conto degli effetti dei cambiamenti climatici sulla disponibilità della risorsa acqua e sugli sviluppi topologici della rete di tubazioni secondo criteri di sostenibilità economica e ambientale, impone di rafforzare i tradizionali criteri di scelta progettuale, a iniziare dalla scelta dei materiali delle tubazioni.

Per garantire un approvvigionamento idrico continuo, adeguato agli usi cui è destinato tramite modalità energeticamente sostenibili, evitando contemporaneamente gli impatti negativi che ne possono derivare, occorre intervenire su tutti i processi legati alla "vita" dell'acquedotto.

La sostenibilità è un concetto particolarmente complesso, suscettibile di diverse definizioni e interpretazioni. Il raggiungimento degli obiettivi di sostenibilità implica l'utilizzo di strumenti valutativi, quanto più possibile, di carattere oggettivo. La complessità degli obiettivi suggerisce di ricorre a indicatori; infatti, quanto più un obiettivo da raggiungere risulta di complessa definizione, tanto più gli indicatori selezionati consentiranno una maggiore accessibilità all'obiettivo della stessa valutazione. E' tuttavia essenziale che tali indicatori siano capaci di sintetizzare diverse aspetti caratteristi della scelta da effettuare, al fine di poter orientare la stessa sulla base degli obiettivi prefissati. Alla luce di tali considerazioni risulta necessario legare la scelta del materiale per tubazioni non solo alle classifiche valutazioni, che tengono in conto l'aspetto idraulico e l'interazione tubo-terreno di posa. Tali criteri standard, infatti, costituiscono la base scientifica per la valutazione del materiale adatto a tubazioni acquedottistiche, in virtù della dipendenza dalle caratteristiche intrinseche, quali la geometria del tubo, e dalle caratteristiche del terreno di posa. L'evoluzione nella tecnologia dei materiali ha introdotto, con il tempo, soluzioni innovative e competitive, le quali rendono ancora più sensibile tale scelta. Inoltre, per le sempre crescenti esigenze in materia di sostenibilità la dipendenza di tale scelta è dovuta a parametri non solo di carattere puramente progettuale, ma capaci di interpretare considerazioni sociali, economiche e ambientali. A supporto di tale considerazione, il Nuovo Codice dei Contratti (D.Lgs 50/2016) introdotto nella normativa italiana, impone la verifica di sostenibilità nelle scelte progettuali mediante l'utilizzo della metodologia *Life Cycle Assessment* (LCA). Tale metodo consente di quantificare gli impatti legati al ciclo di vita dei materiali. L'output del metodo, infatti, fornendo le percentuali d'impatto associate al sistema/prodotto analizzato, si configura come un valido indicatore di sostenibilità della scelta del materiale per tubazioni. Lo studio inerente gli impatti legati al ciclo di vita del singolo materiale (*from cradle to grave*) è infatti esemplificativo del costo ambientale delle operazioni di estrazione, produzione, trasporto, uso, riuso e fine vita. La quantificazione di tale impatto rappresenta l'*output* della procedura di normalizzazione, effettuata mediante il software di calcolo Sima Pro, e ottenuta mediante l'utilizzo del metodo di stima dell'impatto (*Life Cycle Impact Assessment* - LCIA) Impact 2002+, i cui fattori di normalizzazione sono uniformati rispetto agli standard europei. L'unità funzionale è stata fissata in 100 metri lineari di tubazione del materiale scelto con diametro di riferimento DN 600 mm. La fase dell'inventario, *Life Cycle Inventory* (LCI), che rappresenta il substrato di qualsiasi studio LCA, è stata effettuata mediante una rassegna delle principali caratteristiche delle tubazioni, utilizzando il supporto del database Ecoinvent 3, anch'esso integrato in SimaPro. In tale studio sono state analizzate tre tipologie di tubazioni test, esemplificative delle caratteristiche del macrogruppo rappresentativo (Cemento Amianto per Tubazioni Rigide, Ghisa per Tubazioni Semi Rigide e PVC per Tubazioni Flessibili).

ABSTRACT

The water network pipeline materials evolution has introduced market innovations for improving static, hydraulic and cost performance. Over time, to the technical and cost-effective selection criteria of pipelines, related to the materials used, has added environmental assessments linked to the construction and management phases impact. The new scientific and regulatory references have highlighted the need to carry out environmental impact assessments, particularly on the materials and works life cycle. The impacts assessment generated by a product and process, such as the pipeline for water network and integrated water systems management, requires the utilization of a complex technical and scientific supports. In the present paper, a methodology is proposed to introduce new water pipeline selection criteria in the water system sustainability assessment by Life Cycle Assessment (LCA) methodology. In this study some piping materials have been selected and analyzed. The results obtained can also be used for the synthetic indexes construction, which are interest to water system design choice.

Keywords*: sustainable water management, environmental impacts, life cycle assessment, pipe materials, pipe/soil interaction, sustainability criteria*

INTRODUCTION

The water management especially for urban context is a sensitive element to defines the urban ecosystem intrinsic equilibrium and for this reasons it is necessary to pursues a sustainable water resources management. (ASCE, 1998; Sun & Zeng, 2012).

To achieve this goal, it is advantageous to use hydraulic-mathematical modeling to support technical-management operations. In this context, the optimization models are frequently used. These are procedures aimed at optimizing the operational problem solution on the water system**.** The optimal management of these systems requires the improvement of water systems by reducing structural and management deficiencies, the use of unconventional water resources, the risk analysis associated with the vulnerability of drinking water systems, the water resources proper allocation (Maiolo & Pantusa, 2015, 2016; Maiolo et al., 2017; Zhanping & Juncang, 2012; Bai *et alii*, 2013). Even the water resources proper allocation, among the optimization models, is a study context important (Yamout & El-Fadel, 2005; Ni *et alii*, 2014; Maiolo & Pantusa, 2017; 2018a; Carini *et alii*, 2017).

It is also for these needs that it is necessary to use a water resources sustainable management in order to take into account environmental, social and economic goals. The sustainability objectives achievement implies the objective tools use (Maiolo *et alii*, 2005, 2006; Maiolo & Pantusa, 2018b; Loucks, 2002; Nachtnebel, 2002).

In this context, it is necessary to use the indicators to carry out evaluations to support management choices. The complexity and indeterminacy of the aspects that an indicator must interpret implies the need to use an elementary indicators combination in order to obtain a composite index, that is, namely a synthetic index obtained through a mathematical procedure, to interpret complex and multidimensional problems.

The use of these indices types allows an assessed issues clear view, facilitating the analysis, comparison and classification phases of different realities. For the compound indices construction, it is necessary to initially use a parameters normalization process (the indicators are given with measurement units different), then proceed in the weights assignment and in the mathematical model definition for the aggregation procedures (Maiolo *et alii,* 2005, 2006; Marotta & Zirilli, 2015).

The sustainability analysis methodology proposed in the present study represents a necessary reference to the indices integration, such as the In-situ Flexibility Index (ISEC) (Milano, 1996), with the environmental impacts assessment.

In order to maintain high drinking water quality, it is necessary that the materials in contact with it do not affect the physical-chemical and microbiological characteristics. It is therefore necessary to have a particular attention to the piping material choices, also for the interactions with soil. The material choice therefore is linked to geo-morphological considerations regarding the laying soil.

The technological evolution has introduced new piping materials with a performing technical characteristics, sometimes experimenting the several layer composition in a single pipe structure (Iannelli, 1988, 2001; Frega & Maiolo, 2001). These developments have led to the need to compete in a market where investment availability has decreased over time, in cost-benefit ratio terms.

Today the piping material choice requires, in addition to the water features assessment, the soils geological and geotechnical conditions crossed by pipelines, hydraulic conditions and calculation models, but also a sustainability estimate referring to the life cycle (D.M.LL.PP.,1985). In Italian Law, the Legislative Decree n. 50/16 (Legislative Decree N. 50, 2016), introduced in Italian public works law, requires that design also ensures the energy saving, as well as evaluate the life cycle and maintenance impacts.

Therefore, the pipeline materials choice is subjected to new additional criteria, which take into account the sustainability assessment. The material sustainability estimate has to be related to the previous and consequent phases of the exercise. Then the Life Cycle Assessment (LCA) is a useful method for assessing the pipeline material sustainability. The LCA application importance in the water networks sustainable management is highlighted by the TRUST project - Transition to the Urban Water Service of Tomorrow - European Union funded and applied to the drinking water system of the Reggio Emilia Italian city. The innovative aspect of this project is the metabolic model use of such as mass and energy flows synthesis incoming and outgoing from a system. In fact, a metabolic model is capable to synthesizing mass and energy balance since it allows a direct comparison with the organisms metabolism, which extract resources from the environment, process and then return it (Wolman, 1965).

To adapt the metabolic model to the water system performance analysis, it is necessary to study the flow and the transformation process of all material types and the energy, which contribute to the system development and operation (D'Ercole *et alii*, 2014).

In this study, based on the Norwegian University of Science and Technology (NTNU) model, the LCA method was applied to assess the impacts associated with the water intake structure, potabilization, distributing, wastewater collection, purification and discharge phases (D'Ercole *et alii*, 2014). This structure type aims to evaluate the current system performance and all possible future configurations in order to avoid being unable to achieve sustainability in the predetermined time horizon (Di Federico *et alii*, 2012).

In this paper, a new additional criterion for assessing the pipeline sustainability based on LCA methodology is proposed. The work aim is to include, besides standard assessments, environmental considerations to support sustainable water management.

MATERIAL AND METHODS

To optimize the choice of pipe material, adhering to sustainability goals, the interaction between the pipe characteristics and static behavior, but also the interaction between the pipe and the laying soil, needs to be assessed (Datei, 1998).

The pipelines static behavior in water network is due to the soil interaction (in-soil or airborne pipes) and the stresses in relation to the constraint regime with respect to the soil (flat state or beam status). The in-soil pipes diffusion with respect to the airborne pipes causes the in-soil pipe problem to be decisive on the pipeline choice criteria. Therefore, the in-soil pipe static behavior is analyzed considering the pipe-soil system: the pipe characteristics cause a soil different reactions. The pipe static behavior characteristics in relation to the soil are defined primarily respect to its rigidity, namely the aptitude to do not strain due to the stresses. The stiffness is defined by the rigidity modulus depending on the material characteristics (elastic modulus E) and the pipe size (inertia moments I and J, the first dependent on the pipe thickness and the second from the ratio between the thickness and pipe diameter).

The pipe-soil interaction behavior models differ for the trench sizes (narrow or wide) excavation walls (vertical or inclined), lateral filling (limited or indefinite), and thus the deformation and rupture resistance mechanisms. This characteristic defines a classification normally divided into three categories: rigid, semi-rigid and flexible pipes.

The rigid pipe has maximum load under load limited by a final breaking state without significant deformation. The semi-rigid pipe has a maximum load under load limited by a final deformation or breakdown limit state. The hose has a maximum load under load limited by a final deformation limit state.

The cement and fiber-cement pipes are included in the rigid pipes category, iron cast and steel pipes are classified in the semi-rigid category, instead in the flexible pipe category there are a plastic pipes. Synthetically, the water networks pipelines materials and their main features are summarized in Tab. 1:

The pipeline material choice is also related to the laying soil characteristics and these are to complement the static evaluation, according to Saedeleer theory, which schematizes the static behavior of the in-soil pipelines. The soil uniform horizontal reaction q, due to the actions transmitted by the pipe, is proportional to the soil itself deformation Δx:

$$q = K\,\Delta x$$

where K represents a soil rigidity coefficient, defined by the horizontal pressure, which is required to apply to the laying soil to produce a unitary deformation. This coefficient varies from 5 to 120 N/cm^3 and depends on the depth and soil characteristics (Milano, 1996). It is also possible to define analytically the link between the material elastic deformation and the K coefficient, as shown the Tab. 2 last column, referring to a definite diameter class. The pipes which present a EJ/KR^4 ratio values high transmit laterally to the soil a horizontal pressures, which are negligible compared to vertical ones: this aspect defines the rigid pipes

Pipeline Category	Material	Diameter (mm)	Roughness ε (mm)
Rigid Materials	Reinforced cement	n.d.	0,03-10
	Asbestos cement	n.d.	0-0,1
	Fiber cement	70-700	0,03-0,1
Semi-Rigid Materials	Iron cast	70-630	0,05-5
	Steel	10-600	0,015-4
Flexible Materials	PVC	6-630	to 0,03
	PEAD	10-1000	to 0,03
	PP	10-1400	to 0,03
	PRFV	10-4000	to 0,03

Tab. 1 - The main pipeline features

behavior. Conversely, flexible pipes are characterized by a EJ/KR[4] ratio low value.

To guide the piping materials choice, it is necessary to define a criterion which considers the environmental weight. It is therefore important to identify a methodology able to compares the materials types various based on their environmental impacts linked to their life cycle. The Life Cycle Assessment (LCA) (ISO 14040: 14044, 2006) - defines the environmental damage of the considered system lifecycle phases, by assessing the water and energy demand and the production, transportation, use and end life phase contribution (in terms of air emissions, water and soil) referring to individual materials.

The LCA is a useful method to quantify the impact on the environment associated to the pipe material choice. The method output, indeed, provides the evaluation parameters, which, if associated to the traditional pipeline selection criteria, represent further support to guide the choices towards environmental sustainability.

The application of this methodology to the case study allows to compare cradle to grave processes associated with the selected functional unit, that is the single material 1 linear meter. The system boundaries choice such Cradle to Grave allows to have the process full overview, so it can identify the more impact phase referring to the life cycle. The data required by the modeling was chosen from those classified in the Ecoinvent database, and to quantify emissions in the environment, the IMPACT 2002+ method was used. This impact assessment methodology allows to quantify the environmental impacts according to the two approaches:

- midpoint-oriented (based on impact categories);
- damage-oriented (oriented to the damage categories evaluation).

The sustainability assessment using the LCA method is presented in synthetic form for each material category. The environmental cost for these categories is specified compared to the method (IMPACT 2002+) specific categories. The damage categories detail is as follows:

- Human Health - DALY (Disability Adjusted Life Years) - impact categories Carcinogens, Non cancinnogens, Respiratory inorganics, Ionizing radiation, Ozone layer depletion, Respiratory organics
- Ecosystem quality - PDF*m^2*yr (Potentially Disappeared Fraction) - impact categories Aquatic ecotoxicity, Terrestrial ecotoxicity, Terrestrial acidification/nutriphication, Aquatic acidification, Aquatic eutrophication, Land occupation
- Climate Change - kg di CO_2 in the ari - impact category Global Warming
- Resources - MJ - impact categories Non renewable energy, Mineral extraction.

The data are presented in normalized form and the normalization factors are determined by the ratio between the impact per emission unit and the total impact of all substances in the specific category. The normalization factors, for these categories, are calculated per person per year (Humbert *et alii*, 2005) and are presented in the following table:

The software chosen for this application is SimaPro v.8, which contain the Ecoinvent database and the Methods database, where is implemented Impact 2002+ procedure. Because the following assessment is a comparative/qualitative type, it will be considered the same route to be covered by a road transport vehicle for each material. This simplification is useful for delivering the results obtained on an assessment equal scale of transport process referring to the potential environmental damage. In general, the analysis approach is designed to bring out the effective cost, in terms of Human Health, Eco-System Quality, Climate Change and Resources, of the material type.

RESULTS

The proposed methodology has been applied to the material category (rigid, semi-rigid, flexible) selecting a single test material in each class. The choice was based on the most impacted ones

Materials	Nominal Diameter (mm)	External Diameter (mm)	Thickness (mm)	E (N/cm^2)	J (cm^4)	EJ/KR^4
Steel	600	610	6,3	2,6 10^7	0,021	0,0257
Ironc cast	600	635	9,9	1,05 10^7	0,081	0,0438
PVC	600	630	12,4	2,94 10^5	0,159	0,0026
PEAD	600	630	35,7	8,83 10^4	3,792	0,0215
Asbestos cement	600	720	60,0	2,45 10^6	18,000	1,8610
PVRF	600	616	13,1	1,17 10^6	0,187	0,0133

Tab. 2 - The pipeline features referring to the numerical exemplification (Milano, 1996)

Damage categories	Normalization factor referring to 2.0 version	Unit
Human Health	0,0071	Disability-Adjusted Life Year DALY/point
Ecosystem Quality	13.700	Potentially Disappeared Fraction of species over a certain amount of m2 during a certain amount of year PDF.m2.y/point
Climate Change	9.950	kg CO2 into air/point
Resources	152.000	MJ/point

Tab. 3 - Normalization factors for the Impact 2002+ damage categories related to Western Europe (Humbert et alii, 2005)

and choosing among these widely used ones. The test material choice carried out for each type was oriented to the technical features which synthesize the represented category. To make the evaluation homogeneous, was referred to the same nominal diameter (ND = 600 mm) on the Tab. 2 basis.

- Rigid material

In the rigid materials category, the LCA analysis focused on asbestos cement pipes (AC). This choice, although the adverse impacts on human health which make the AC unsustainable are known, derived from the analysis utility in order to carry out the comparative assessment with the other materials. For this reason, in this analysis is expected the currently piped AC pipes total replacement goal.

The AC was chosen as the LCA analysis material also for known impacts related to it and for the technical characteristics, which synthesize the category. The AC pipes have certain peculiarities in terms of strength/durability, which can be summarized as follows:

- not very high resistance to mechanical abrasion (depending on the compactness degree)
- non-very high resistance to the chemical aggression.

The method output is summarized by Tab. 4:

- Semi-rigid materials

In the semi-rigid materials category, the LCA analysis focused on iron cast pipes. The iron cast pipes have certain peculiarities in terms of strength/durability, which can be summarized as follows:

- good resistance to mechanical abrasion
- discrete resistance to the chemical aggression.

The method output is summarized by Tab. 5:

- Flexible materials

In the semi-rigid materials category, the LCA analysis focused on PVC pipes. The PVC pipes have certain peculiarities in terms

Damage category	Total (‰)	Raw materials (‰)	Energy (‰)	Transport (‰)
Human health	13,124	12,525	0,579	0,017
Ecosystem quality	1,868	1,798	0,0582	0,011
Climate change	20,496	19,751	0,731	0,015
Resources	8,602	7,823	0,763	0,016

Tab. 4 - Normalized Impact for damage category referring to the CA pipeline

Damage category	Total (‰)	Raw materials (‰)	Energy (‰)	Transport (‰)
Human health	4,136	0,975	2,841	0,011
Ecosystem quality	0,261	0,086	0,135	0,012
Climate change	2,571	0,421	2,028	0,015
Resources	2,593	0,352	2,133	0,016

Tab. 5 - Normalized Impact for damage category referring to the iron cast pipeline

Damage category	Total (‰)	Raw materials (‰)	Energy (‰)	Transport (‰)
Human health	0,763	0,183	0,563	0,018
Ecosystem quality	0,073	0,012	0,049	0,012
Climate change	0,895	0,176	0,704	0,015
Resources	1,066	0,308	0,742	0,016

Tab. 6 - Normalized Impact for damage category referring to the PVC pipeline

of strength/durability, which can be summarized as follows:

- good resistance to mechanical abrasion
- very well resistance to the chemical aggression.

It is useful to specify that plastic piping materials have poor mechanical quality and the mechanical properties decay is closely related to temperature.

The method output is summarized by Tab. 6:

The comparison between the results obtained by applying the LCA method for the three case studies is presented in Fig. 1.

The most significant peak is associated to the Climate Change for AC pipes. The damage category impact, expressed in kg of CO_{2eq}, is justified by the high mechanization of the production process, dependent on the equipment (weighing, additives distribution, water and humidity meter) whose required energy is not attributable to renewable sources.

The iron cast production process contribution, in terms of Human health category, is related to the CO_2 emissions in the environment related to production mechanisms. The CO_2 emission can be very damaging because it obstructs the red blood cell oxygenation process. It is immediately noted that PVC provides a lower contribution to AC and iron cast for each damage category, therefore, it represents the more performing solution.

The proposed results represent a qualitative evaluation, useful for comparing the materials performance. The impacts quantification by the LCA method is a supporting indicator for the pipe material choice and can not be replaced the standard criteria. Because in these assessments, the economy maximum criterion is fundamental (Frega, 1984), the LCA evaluation ensures a useful support, integrating the “best sustainable choice” criterion in the pipe material selection.

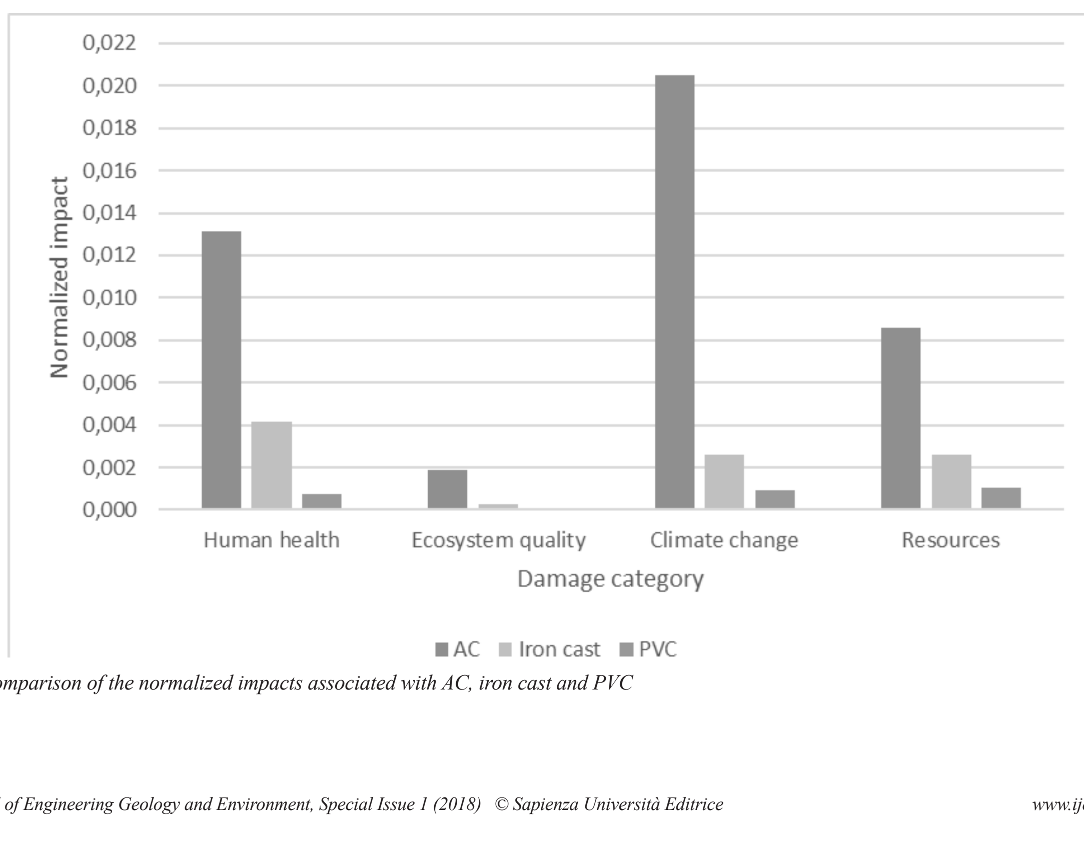

Fig. 1 - Comparison of the normalized impacts associated with AC, iron cast and PVC

In order to confirm the results obtained, the 12 lifecycle assessments referring a various piping tipology, with different uses, were conducted by VITO (Flemish Institute for Technology Research) on Teppfa behalf (The European Plastic Pipes and Fittings Association). This study is synthesized in EPD certifications, subjected to critical evaluation by the denkstatt company (multinational in the Environmental Protection, Management Systems, Social Development, Sustainability Consulting field). In summary, these studies result highlight the best environmental performance of plastic pipes in comparison to traditional materials:

- on Global Warming and Ozone Layer Depletion impact categories the plastic pipes have a yield of about 80% more than competing systems
- the extrusion process contribution (linked to the metal materials) is higher than the injection process (linked to the plastic materials).

The plastic pipes using advantages, such as PVC, also is relative to the limited investment and repair costs, guarantee on the drinking water quality, a high durability in service life (Piltz *et alii*, 2010). The plastic pipes represent the more competitive choice for the life cycle performance, but can release organic and phosphorous compounds which facilitate microbiological regeneration and biofilm formation (Yu *et alii*, 2010; Lehtola 2004; 2005).

The LCA procedure application for pipeline life cycle analysis is a useful evaluation to guide design choices. This evaluation is a valid support to classic static and hydraulic evaluations for the most sustainable pipeline type choices. The LCA approach can be considered as complementary to the usual static and hydraulic checks which allow to express an useful correlations for specific analyzes.

CONCLUSIONS

The pipes material choice in a water network is oriented to the design conditions based on hydraulic, geological, static and economic evaluations. The materials evolution has brought significant improvements in the pipes hydraulic and static behavior. Increasing environmental sensitivity has mainly affected the assessment criteria of design alternatives in terms of environmental sustainability. The LCA method introduction, as a complementary and orienting tool, is a useful technical support for measuring the pipeline materials sustainability. This analysis proposes a comparison methodology for different materials using in the water network pipes, based on the LCA method, and provides an additional criterion which completes the evaluations for design choices. The methodology and the results obtained can also be used for the sustainability indices definition.

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