Multicriteria–decision making in the sustainability assessment of sewerage pipe systems

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Abstract

A method based on the value analysis and the multi-attribute utility theory is applied in this study to assess the sustainability of both concrete and plastic sewerage pipes. This procedure makes it possible to minimize subjectivity in the process of quantification and comparison of alternatives. To do so, the requirements tree is defined to construct a non-dimensional sustainability index for each alternative, by means of value functions and weights assigned to their different components. The model was developed and tested through seminars and questionnaires solved by specialists in the field and senior managers in the Spanish public sector.

The model is used to assess the sustainability of 8 alternatives including rigid reinforced and non-reinforced concrete pipes as well as flexible polypropylene, polyethylene, polyvinyl chloride and glass-fibre reinforced polyester pipes. Nominal diameters of 400, 800, 1200 and 2000 were chosen as those representatives for urban and rural sewerage networks.

The proposed model guarantees a high degree of objectivity and clarity to deal with the sustainability analysis applied in this case to sewerage pipes, but also applicable to other areas. The sustainability indexes were similar for diameters of 400 mm and below, independently of the material. This fact justifies the penetration of the flexible tubes perceived in a market segment that has been dominated so far by the rigid pipes technology. However, concrete solutions are clearly better in terms of sustainability for wider diameters.

The organization of seminars with specialists and the use of the Analytical Hierarchical Process for the attribution of weights proved to be a suitable and satisfactory combination to deal with the quantification of sustainability in this case and its extension may also be useful in other areas.

Keywords

MCDM, MIVES, AHP, urban networks, sewer, cities, economic, environmental, social.

1. INTRODUCTION

At present, over half of the global population lives in cities (The World Bank 2014) and estimations for 2050 predict that it will grow (UNESCO 2014). Cities have both positive and negative sustainability impacts. On the one hand, urban settlements provide social and economic facilities and services but, on the other, they also have far-reaching ecological impacts (Diamond 2005). The global environmental impact of cities varies around the world (Newman 2006), as these consume the 75% of the world's resources and produce the 75% of CO_2 emissions (Bouteligier 2013). The major part of this impact can be attributed to the thousands of kilometers of various service networks in both urban and interurban areas of each city (Rostum 2000). This means that the sustainable management of urban and interurban networks must be taken into account to meet the essential requirements of a growing population (Gleick 1996; Short *et al.*, 2012).

Underground sanitation networks are difficult to access and their most frequent problem is leakage that cannot be easily detected or fixed and that has serious consequences. For example, leakage in drinking water networks increase water consumption in the use phase, while leakage in sewer pipes can contaminate the water table (Galvis et al 2014, EU Water Framework Directive 2000). As in all subterranean systems, high economic costs are attached to the renewal of sewerage networks (Shook & Bell 1998). However, water is a primary human need under increasing demand in growing urban areas that has to be supplied to all consumers under proper sanitary conditions. To do so it is essential for cities to control the urban water cycle (UWC).

The reality is that endemic problems in underground networks are swiftly worsening, while the proliferation of services (drinking water, wastewater, electricity, gas, telephone, television and broadband internet services) simply increases routine and emergency maintenance tasks. Besides, most of these primary networks that carry increasingly scarce resources have become old and even obsolete (Kleiner 1997, Rostum 2000). Some countries, such as Brazil, where significant sewerage networks are still to be built, have funded research projects for their optimization (Nascimento 2014). The choice of the best piping material will be crucial, if only for sustainability, among other factors. In this regard, greater knowledge of sewer pipe technology and manufacturing techniques now offer several alternatives (e.g. concrete, PVC, PE, PP, PFRV) appropriate for different conditions with different degrees of satisfaction (Viñolas 2010, Petit-Boix et al 2014).

Concrete and plastics (PE, PP, PVC, PFRV, among others) are the main materials for the manufacture of piping. The latter provide a flexible structure while the behavior of concrete is rigid. In general, plastic tubes are of reduced weight and therefore require less machinery and labor for transport, handling and installation. In addition, their susceptibility to aggressive chemical and bacteriological agents found in the effluent that circulates through the sewerage tubes is practically non-existent. However, their mechanical properties weaken over time, due to the inherent ageing processes of the material. Likewise, rigorous compaction of the backfill is required that in consequence affects economic factors (machinery) and the completion of their installation.

On the contrary, concrete pipes show a more rigid behavior and their mechanical resistance is not so dependent on the quality and execution of the backfill. In addition, if the concrete pipes crack while in service, this has little effect on their durability, provided that the design and execution of the reinforcement (usually steel rebars) is sufficient to keep the crack openings within the established design values. On the contrary, their weight is notably higher in comparison with the plastic solutions, requiring more powerful means of transport and on-site handling. In short, notable technical differences can be appreciated between these types of materials, which should be taken into account in the selection process.

Recent environmental impact studies on drinking water pipelines (Sanjuan-Delmás et al., 2014) and sewer construction (Petit-Boix et al., 2014) are worth mentioning. Since the 1990s, environmental, economic and social impacts have been identified as the three principal aspects of sustainable development (ICLEI 1994). In this context, the technical literature contains numerous Multi-Criteria Decision Making (MCDM) methodologies to assess water resource management (Le Gauffre et al., 2007, Hajkowicz 2007, Koo and Ariaratnam, 2008, Hajkowicz 2008, Koo et al., 2009, Nussbaumer, 2009, Anda et al., 2010, Yeh & Xu 2013) and, even, sustainability assessment models for underground infrastructure projects (Koo et al. 2009). However, these studies are rather generalist and have not been adapted to the analysis of sewer pipe materials in terms of the three previously mentioned aspects. An integrated sustainability assessment method has therefore been developed, based on the MIVES integrated value model for sustainable assessment (Aguado et al. 2012).

MIVES is a Multi-Criteria Decision-Making (MCDM) method developed at the start of the new Millennium that has already been applied in several real projects (Jato-Espino *et al.*, 2014). It assisted, for instance, in technical and economic decisions during the construction of hydraulic infrastructure and Line 9 of the Barcelona Metro (Ormazabal *et al.*, 2008). Likewise, it formed the basis of a method that analyzed different building technologies for schools (Pons *et al.*, 2012), reinforced concrete columns for supporting slabs (Pons *et al.*, 2013), investment priorities in hydraulic structures (Pardo and Aguado 2014) and wind turbine support systems (de la Fuente *et al.*, 2014). In addition, a probabilistic MIVES method has been developed and applied for the design of large, complex buildings (del Caño et al., 2012). Additionally, a simplified version of the model has been included in the current version of the Spanish structural concrete code EHE – 08 (Aguado et al. 2012).

In this context, the **objectives** of this article are (1) to propose a method that incorporates the most representative aspects in the selection process of the most sustainable material for sanitary piping, while minimizing the subjectivity of the decision-making process; and, (2) to evaluate the sustainability of various representative diameters for sewerage piping manufactured with alternative materials now available on the market.

2. METHODOLOGY

2.1 Introduction

The main initial phases of the MIVES methodology consist of a definition of the system boundaries and the decision tree. In the first phase, the temporal axis, the components axis and the general aspects are determined. In the second phase, all the aspects are organized around the branches of the decision tree. The first level of the tree contains the most general aspects (requirements), the second level contains the criteria and, the third level, the most specific aspects (quantifiable indicators). The definition of the tree also implies setting the value functions to transform the indicators from physical units (kg, ºC, hours, $, points,…) into value units (from 0 to 1) and the weighting and aggregation procedure of the different tree levels, as will be explained in greater detail later on.

The working method in this study included the completion of various seminars with experts from the industrial sector and the public administrations, represented by senior managers on their decision-making bodies, with the aim of establishing the requirements, criteria, indicators and weights that constitute the sustainability evaluation method of the sewerage pipe networks described in this article.

2.2 System boundaries

Numerous factors influence the sustainability of sewerage pipe networks. Hence, certain limitations have been placed on the system that will be studied, so as to ensure that its parameters are representative. In this regard, the discriminant factors were identified from among the different alternatives to conduct an integrated analysis of all possible components and phases of the life-cycle of the pipes.

The requirements under consideration are the three basic aspects of sustainability (economic, environmental and social) (United Nations 2005), plus a fourth associated with functionality. Likewise, the components considered in the analysis are the pipes, their special components and the joints.

The life-cycle of a pipe is conditioned by: (1) the extraction of materials for the manufacture of the pipe; (2) its manufacture; (3) its transport; (4) its installation; (5) the backfill/embedment of the drainage trench; (6) the useful life of the pipe (use and maintenance); a minimum of 50 years in all cases, and; (7), its deconstruction.

The phases of life-cycle analysis (LCA) under consideration cover the reception of materials into the factory up until the pipe installation phase on site. However, two exceptions may be noted: on the one hand, the LCA covers the extraction of raw materials for the manufacture of the constituent materials of the pipes for the indicators of $C0_2$ emissions and consumed energy. On the other hand, aspects related to the functional requirements are centered on the life-cycle phase (service life) of the pipes. These two exceptions are justified by the fact that they are the most clearly discriminatory aspects between the piping alternatives.

During the seminars, it was concluded that a 1 km length of the network would be a sufficiently precise definition of a functional unit for analysis. In addition, it was agreed that the terrain where the trench would be excavated would be of standard quality, consisting of gravel and clayey or muddy sands (ATV-127). Both aspects are crucial for the evaluation of economic and functional aspects.

Finally, an interurban network was considered and, therefore, aspects such as, for example, installation (and repair) time and contamination of the water table were respectively assigned different weights than would otherwise have been assigned for urban and rural networks. In any case, it is important to underline that the proposed method can evaluate networks both in urban and rural areas by adapting the weights and/or value functions.

2.3 Requirements tree

2.3.1 Introduction

The construction phase of the decision tree is the most important part of the process. Thus, the coherence, representativeness and objectivity of the criteria and indicators under consideration will guarantee the goodness and credibility of its results. The detailed items of the decision tree, formed of the 4 previous requirements, 10 criteria and 14 indictors, for the sustainability evaluation of the sewerage pipes (Parrot 2008; Viñolas 2010) appear in **table 1** below.

In addition to the seminars with experts for the construction of this specific decision tree in the case study (**table 1**), current academic and technical publications related to sewerage pipes were researched (ATHA 2000; CEDEX 2006; UNE 127916:2004; UNE 53331:1997; Balairón 2006; ACPA 2011; Carleo et al 2012; Plastics Pipe Institute 2008; de la Fuente et al. 2012; de la Fuente et al. 2013; Mohammed *et al.* 2014; Peyvandi *et al.* 2014), as well as sustainability studies on other materials and components (Baldasano *et al.* 2005, Petit-Boix *et al* 2014 Sanjuan-Delmás *et al* 2014).

2.3.2 Weighting of requirements in the decision tree

The weightings attached to the indicators of each criterion, to the criteria of each requirement and to the four requirements of the decision tree establish their relative importance. These weights therefore determine the assessment of the aspects considered within the system boundaries and customize the general requirements tree to the specific conditions of the case of study.

Table 1. Decision Tree

Requirements	Criteria	Indicators
R1. Functional (11.1%)	C1. Pipe dysfunction (33.3%)	I1. Surface degradation (100%)
	C2. Joints dysfunction (33.3%)	I2. Problems in joints (100%)
	C3. Mechanical capacity (33.3%)	I3. Extra capacity (100%)
R2. Economic (33.3%)	C4. Cost (80%)	I4. Total cost (100%)
	C5. Execution time (20%)	I5. Time (100%)
R3. Environmental (33.3%)	C6. Emissions (20%)	I6. CO_2 emissions (100%)
	C7. Resources (60%)	I7. Prime materials (33.3%)
		I8. Water (33.3%)
		I9. Energy (33.3%)
	C8. Adaptations (20%)	I10. Sensitivity (100%)
R4. Social (22.2%)	C9. Labor safety (25%)	I11. Risk of accidents (100%)
	C10. Affectations (75%)	I12. Time (33.3%)
		I13. Pollution (33.3%)
		I14. Vulnerability (33.3%)

Analytic Hierarchy Process (AHP) methodology (Saaty, 1980) was used to set the weights (**table 1**), guided by the information gathered from the experts at the seminars. These weightings respond to a general interurban sewerage network that is neither specifically for a rural nor for an urban setting. It may be seen that: (1) the administrations assign similar weights to both the environmental and the economic aspects and somewhat higher ones to the social aspect; (2) the importance of the functional requirement is secondary, as the administrations assume that strict compliance with the standards is sufficient and, therefore, any improvement in the technical field is of marginal interest. This viewpoint is mainly a consequence of any such improvements (mechanical capability, for example) becoming effective, in theory, in a future scenario, in which the beneficiaries of the administration will be other people due to the successive renewal of technical staff.

2.3.3 Functional requirement

The criteria of the functional requirement are dysfunctional pipes (C1), dysfunctional joints (C2) and the added capabilities (C3).

The purpose of criteria C1 is to take potential deterioration on the pipe surface into account through indicator I1. This indicator presents an assessment of wear on both the interior surface as a consequence of the environment and chemical agents that circulate inside the pipe and on the exterior surface in contact with the terrain, the composition of which contains aggressive elements for the tube material and deterioration due to abrasion may even occur. For example, sulfur reduction can occur in sewer wastewater that stagnates or flows at low velocity inside concrete piping, which can affect both the concrete and its reinforcement (CEDEX, 2006). The concrete layer is usually thickened and/or plastic sheets are used to line the interior of the pipe to guarantee its useful life; all of which therefore increases the cost, the number of operations and the environmental impact linked to the materials. On the other hand, plastic materials in contact with certain substances present in the soil or in the liquid carried in the pipes will age, causing brittleness and weakening of their structural capability.

Criteria C2 is intended to take account of the technical risks of failure of the joints between the pipes and/or with other components (I2) and is the indicator that evaluates the potential for damage in these discontinuous zones. Owing to their discontinuity and because these areas with less rigid, the joints have a greater risk of local failure, possible leaks and the appearance of other problems, because they may be subjected to differential stresses that are difficult to estimate (or even to evaluate) in the calculation; they are, in short, problematic zones. In this regard, flexible pipes present a greater probability of failure in comparison with rigid tubes, because of their greater deformability; in addition, it is also found that, regardless of the material, the risk of deformation increases with the diameter of the tube, because of the difficulties associated with the increased weight and with maneuverability in reduced areas (inside drainage trenches, for example).

Finally, criteria C3 includes the indicator of added mechanical capability (I3). This refers exclusively to structural aspects and rewards the fact that one type of pipe can withstand the conditions established in the construction project with a higher safety coefficient than other types (I3). Evaluation of this resistant capability should take the overall behavior-structure of the terrain into account and, therefore, the type of terrain, its compaction and the type of installation.

In this regard, all the acceptable alternatives for the established conditions of the site (type of drainage trench and loads) should strictly comply with the requirements set out in the regulations; however, some pipes can exceed these requirements, either because the safety coefficients for each type of pipe are different or because the resistance classifications of the pipes are not the same (it is not standard practice to manufacture a specific pipe for a specific strength of concrete) and, therefore, there is always leeway with regard to the required specifications, which will depend on the extent of the range of resistant categories of each type of tube.

In addition, plastic pipes are, for example, less likely to be damaged by soil compaction techniques and the resistance characteristics of the terrain. This difference implies an advantage over various factors that can occur throughout its useful life: higher than expected stress than at the design stage (soil conditions that are worse than expected in the design phase, for example). In these cases, if the typology under study has a higher resistance capability, there is a greater probability of contingencies of this sort.

It should be stressed that criteria C3 includes no hydraulic aspects as these are not discriminants in the case study. In this regard, although it is true that concrete pipes, for example, usually present higher internal roughness coefficients than plastic tubes in an initial comparison (before entering into service), this difference is lessened when a representative section of the network is considered, as biological flora and decantation that occur during the life-cycle of the network determine the internal roughness of the tube and, in consequence, the loss of hydraulic load. These deposits occur in the same magnitude regardless of the type of pipe (UPV, 1998).

2.3.4 Economic requirement

The economic requirement is represented by two criteria: cost (C4) and time (C5). Criteria C4 includes a single indicator (I4) that evaluates the total cost, the sum of all costs associated with the manufacture of the pipe, which depends on the pipe material, its transport and installation. These last two aspects depend principally on whether the pipe is rigid or flexible, as the differences between both classes of pipe are related to their weight, which is the principal factor that governs both costs.

On this point, (CEDEX, 2006; Hernández, 2002) establish that both typologies usually require trenches with similar geometric characteristics for the same pipe diameter. In consequence, excavation costs are not a discriminant factor. However, it should be mentioned that the degree of soil compaction following the installation of the pipe is more demanding for flexible pipes, as their mechanical capability depends, to a great extent, on the soil-structure interaction. Nevertheless, in terms of economic costs related to the installation, a standard level of compaction specified as Proctor Normal PN ≤ 85% was considered for the different pipe typologies. If differential compaction strategies have to be considered in accordance with the type of pipe, the associated cost in the same indicator (I4) may be added.

Finally, criteria C5 covers the temporal variable in terms of the execution time associated with each alternative tube (I5). This indicator includes, on the one hand, the time the supplier needs to deliver the alternative selected in the plans, as the manufacturer may have it in stock (if frequently used) or may have to manufacture it *ad hoc* for the specific site (standard in concrete tubes, for example), depending on the diameter, material and resistant category that is selected, thereby increasing the time and the execution period in the last case. Moreover, the execution time on site should be included in each alternative, which differs in accordance with the weight and length (number of joints) of the piping.

Indicator I5, even though it has a temporal connotation, is relevant at an economic level according to the Project Managers who participated in the seminars and who confirmed that the longer the total required time, the greater the associated costs of the work and the greater the risks of delay (economic penalties).

2.3.5 Environmental requirement

The environmental requirement has three principal branches, which are the emissions criteria during manufacture and the transport of each pipe (C6), the resources used in the system (C7) and the corrective measures of an environmental nature that the manufacturer applies to the production area (C8).

The purpose of criteria C6 is to assess the emissions, with a view to encouraging their reduction. To do so, the indicator for CO_2 emissions is introduced (16), a key point today and important for any sector at a global level (greenhouse effect). The following points were included (Baldasano *et al*., 2005) in the analysis of the life-cycle: (1) the extraction of materials, (2) manufacture of the pipe, (3) its transport, and (4) installation. Excavation and backfilling of the trench were not considered in the evaluation of $C0_2$, as in all cases the trench was assumed to have a representative, average geometry, with the same level of compaction.

The purpose of criteria C7 is to minimize the consumption of resources in terms of raw materials for completion of the installation (I7), water (I8) and energy (I9).

The evaluation of indicators I6 and I9 was carried out through a lifecycle analysis for each of the alternative pipes. Indicator I8 was evaluated in terms of the percentage of recycled water (rain water or recycled wastewater in the factory) as a proportion of total water consumption for the manufacture of the pipe, so as to promote sustainable usage. Likewise, indicator (I7) was evaluated in relation to the backfilling material that is employed following the installation of the pipe. The indicator promotes those solutions that include the use of excavated earth as backfilling material and penalizes those solutions that require additional material to complete the trench and to guarantee the mechanical requirements of the system.

Finally, the inclusion of indicator I10 under criteria C8 has the purpose of encouraging an environmental commitment among pipe manufacturers and is intended to evaluate their environmental sensitivity. This indicator covers all those preventive measures that the manufacturer introduces in the factory to reduce the environmental impact (silencers, anti-dust barriers, rubber seals, among others), measures for internal recycling, waste controls and the dosage optimization of materials. These would be additional measures, not considered in the other indicators under this requirement, which could be evaluated through the possession of relevant environmental certifications.

2.3.6 Social requirement

The social requirement criteria adopted for this study were labor safety (C9) and third party affectations (C10). In this case, the phases with a direct effect on this requirement are: (1) manufacture, (2) transport, and (3) laying of the pipes, which are principally influenced by the weight, material and type/number of unions associated with each alternative. None of the three following phases were included: (1) extraction of the materials for the manufacture of the pipes; (2) their deconstruction, if outside the boundaries of the system (section 2.1); and, (3) excavation-backfilling of the trench, with the same reasoning as for the earlier requirements.

Criteria C9 is composed of indicator I11 with which the potential existence of occupational risks in the production and execution phase is evaluated. Subsequently, criteria C10 evaluates: (1) interruptions owing to repairs (I12) that affect the network supply and other services that are directly involved during the repair work (traffic, lighting, among others); (2) contamination of the water table (I13), which can apply to those environments in which water is extracted for public/private consumption and irrigation (rural areas, for example); and, (3) the vulnerability of the pipe (I14) to future work on the superstructure (widening of the roadway, construction of underground services, among others). In this regard, earth movements and overloading may affect more robust and rigid solutions less, despite the heaping of materials/heavy machinery involved in the work and not foreseen in the initial design of the network.

3. STUDY CASE

3.1. Alternatives under analysis

A total of 8 alternative pipes (**table 2**) with different nominal diameters (D_n) and constituent materials were analyzed in terms of their sustainability using the MIVES methodology described in the preceding sections. These alternatives are representative of urban, rural and interurban sewerage systems for a high range of wastewater flow and classes of pipe resistance.

Accordingly, piping with a D_n of 400, 800, 1200 and 2000 mm were selected. Likewise, the resistant classes (in terms of load-bearing capacities for the concrete pipes or circumferential stiffness for the flexible pipes) were chosen, so that the material alternatives for each D_n were of an equivalent mechanical capacity. The weight per meter (W) is included in the same **table 2**.

The following alternatives were considered: 400 mm – D_n unreinforced concrete pipes (UC-400); steel bar reinforced concrete pipes with a D_n of 800 mm (SBRC-800), 1200 mm (SBRC-1200) and 2000 mm (SBRC-2000). The concrete pipes were classified in accordance with standard EN 1916:2002. In this regard, the UC pipes with D_n = 400 mm responds to a class R (ultimate load bearing capacity F_n of 135 kN/m^2). The SBRC pipes under consideration are categorized as Class IV (service load F_c of 100 kN/m^2 and F_n = 150 N/mm^2). The piping should withstand these loads in the three edge bearing test described in standard UNE EN 127916.

Table 2. Piping specifications

D_n (mm)	Material	D_i (mm)	h (mm)	W (kg/m)	**CODE**
400	UC	400	60	240.0	UC-400
	PP	400	50	8.3	PP-400
800	SBRC	800	100	705.0	SBRC-800
	PVC	748	26	8.9	PVC-800
1200	SBRC	1200	140	1395.0	SBRC-1200
	PE	1030	85	67.5	PE-1200
2000	SBRC	2000	215	3650.0	SBRC-2000
	PRFV	1958	45	384.0	PFRV-2000

Moreover, 400 mm-D_n polypropylene pipes (PP) and 800 mm-D_n chloride polyvinyl chloride (PVC) pipes were also assessed, both with a circumferential stiffness of SN 8 and a compact cross section. Finally, a 1200-D_n polyethylene (PE) pipe with a dual wall corrugated section profile (SN 8) and a 2000-D_n glass-fiber reinforced polyester (PRFV) pipe (SN 10000) and a nominal pressure of PN 10 were included. As can be seen, this last pipe can support internal pressure as well and, therefore, its mechanical capacity is much greater than required; however, there are no other flexible pipes with a similar D_n that can bear the loads that are required in this study.

New experimental environmentally friendly pipes such as those incorporating recycled aggregates (Rahman 2014) were not assessed in this research, although the same method could easily be adapted for their analysis.

3.2. Hypotheses and basic assumptions

The mechanical analysis of each alternative was performed using the software presented in (de la Fuente 2008), which is intended to facilitate the design and verification of sewerage pipes according to various standards (UNE 53331) for flexible pipes and (EN 1916:2002) for rigid (concrete) pipes. Additionally, the following assumptions applied:

1. The representative values of the elastic moduli over 50 years for each of the flexible pipes were as follows: E: 5730 N/mm^2 (PRFV) (DIN-16961-2); E: 1750 N/mm^2 (PVC); 150 N/mm^2 (PE); and E: 120 N/mm^2 (PP) as per (UNE 53331).
2. Safety class type A for the flexible pipes: existence of phreatic level, reduction of the service level and severe economic impact in case of damage.
3. Installation in a vertical trench on a granular embedment at an angle of 60º with respect to the centre of the pipe. The terrain coverage is twice the D_n above the crown of the pipe, except for those with D_n = 2000 mm, for which 3.0 m is considered. Likewise, the width of the trench allowed for 0.20 m on each side of the pipe; a minimum value that guarantees ease of installation and soil compaction.
4. A moderately cohesive terrain consisting of gravel and clayey or muddy sands. Soil compaction carried out after backfilling at an SP ≤ 85%.
5. A representative traffic load value of 5 kN/m^2.

So as to cover the complete range of situations, ideal conditions (scenario A), average conditions (scenario B), and, poor conditions (scenario C) were all assumed for the evaluation of water consumption (I8) and the environmental sensitivity of the production plant (I10).

The evaluation of the indicators for CO_2 emissions (I6) and for energy consumption were based on studies completed by (Baldasano et al. 2005; Specht & Lorenz 2008; Häkkinen & Mäkelä 1996), in which they propose average values for these variables in relation to each component of the lifecycle analysis.

3.3. Quantification of the indicators

Having considered the analytical hypotheses established in section 3.2 and the additional information gathered at the seminars and surveys, the evaluation of each indicator is presented in **table 3.**

Quantification of indicators I1-I2, I5, I11-I14 was done through 16 surveys sent to individuals with technical expertise in the design and execution of sewerage networks. The respondents were asked to evaluate the indicators on the basis of a scale of rising intensity graded by the following points: very low, 0 points; low, 2 points; medium, 4 points; high, 6 points; very high, 8 points; all of which previously defined in the seminars.

The remainder of the indicators were approached by taking into account the points presented in sections 2 and 3.2.

3.4. Value functions

A value function was proposed for each of the indicators (Alarcón et al., 2011) that transforms the units of measurement of each indicator into an adimensional value unit somewhere between 0 and 1. These represent the valuation from zero to maximum satisfaction, respectively. This scale of adimensional values is necessary to even out the sum of the values of each indicator (V_i), the physical units of which will depend on the nature of the evaluation.

Table 3. I1-I14 indicator values for each pipe alternative

Indicators	D_n (mm)	**400**		**800**		**1200**		**2000**	
	Materials	**UC**	**PP**	**SBRC**	**PVC**	**SBRC**	**PE**	**SBRC**	**PRFV**
I1. Surface degradation (points)		6.25	2.13	5.88	2.63	5.75	2.75	6.75	2.38
I2. Risks at joints (points)		0.88	4.88	1.63	5.75	2.63	6.38	3.38	2.88
I3. Extra capacity (kg/m²)		3500	100	5000	300	5000	0	5000	700
I4. Total cost (€/m)		24.3	54.8	93.0	153.3	165.7	359.8	420.9	1370.9
I5. Execution time (points)		2.63	0.50	4.25	2.13	5.75	2.63	7.00	6.13
I6. CO_2 emissions ($kgCO_2$/m)		22.3	14.4	65.7	215.3	129.7	113.4	339.5	940.0
I7. Raw material (points)		1.00	0.67	1.00	0.67	1.00	0.00	1.00	0.67
I8. Recycled water (%)	Scenario A	100	100	100	100	100	100	100	100
	Scenario B	50	75	50	75	50	75	50	75
	Scenario C	0	50	0	50	0	50	0	50
I9. Required energy (MJ/m)		144	48	423	756	837	828	2190	3300
I10. Sensitivity (points)	Scenario A	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Scenario B	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Scenario C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
I11. Labor risks (points)		2.88	0.50	3.88	2.13	6.50	3.13	7.75	5.50
I12. Repair time (points)		2.63	0.5	4.25	2.13	5.75	2.63	7.00	6.13
I13. Water table contamination (points)		2.56	3.63	3.13	4.19	4.13	4.94	4.94	5.81
I14. Vulnerability (points)		2.50	6.75	2.00	6.25	2.50	7.25	2.88	5.50

The value function in use was defined through five parameters with which the sensitivity function of the indicator may be adapted, thereby obtaining different forms: S-shaped, concave, convex, and linear. The parameters that define the type of function are: K_i, C_i, X_{max}, X_{min}. y P_i (eq. 1) for growing functions.

$$V_{ind} = B\left[1 - e^{-K_i\left(\frac{|X - X_{min}|}{C_i}\right)^{F_i}}\right] \qquad (1)$$

In eq. 1, X_{min} is the minimum abscissa value in the indicator interval that is assessed; X is the abscissa value for the assessed indicator; P_i is a shape factor which defines whether the curve will be concave (P_i<1), convex (P_i>1), linear (P_i = 1) or S-shaped (P_i>1), which will approximately determine the slope of the curve at the inflexion point; C_i approximates the abscissa at the inflexion point; K_i tends towards V_i at the inflexion point; B is the value that keeps the function within the range from 0 to 1 and can be assessed by means of eq. 2, X_{max} being the abscissa value of the indicator that gives a response value of 1 for increasing value functions.

$$B = \left[1 - e^{-K_i\left(\frac{|X_{max} - X_i|}{C_i}\right)^{F_i}}\right]^{-1} \qquad (2)$$

Decreasing functions may also be used that take the maximum value at X_{min}, for which purpose eq. 1 may be used by substituting X_{min} for X_{max}.

The satisfaction/value of the indicators involved in the present study can be satisfactorily represented with decreasing functions (D), these being linear (DL), concave (DC) or S-shape (DS). In this regard, the data and the form of each value function is presented in **table 4,** a detailed justification of which may be consulted in (Viñolas 2010).

4. RESULTS AND ANALYSIS

Taking into account the quantification of each indicator (**table 3**), the value functions and their respective parameters (**table 4**) and the weights of the requirements tree shown in table 1, the value of each requirement (**table 5**) and the global sustainability index (table 6) for each alternative may be obtained.

Table 4. Parameter values for the different indicators

Indicator	**Units**	D_n	X_{min}	X_{max}	C	K	P	**Shape**
I1, I2, I5, I11-I14	Points	Independent	0	8	1	≪1.00	1.00	DL
I3. Extra Capacity	kg/m^2	Independent	0	5000	1000	0.70	0.55	DC
I4. Total cost	€/m	400	170	20	95	0.95	1.95	DS
		800	405	50	225	0.95	1.95	DS
		1200	760	150	390	0.95	1.95	DS
		2000	1350	400	530	0.95	1.95	DS
I6. CO_2 emissions	kgCO_2/m	400	109	14.78	35	0.95	1.95	DS
		800	321	165	165	1.00	1.25	DS
		1200	635	115	300	1.00	1.95	DS
		2000	1665	725	725	1.00	1.75	DS
I7. Raw materials	Points	Score as a function of the type of backfill material that is needed, evaluated by cohesion: non cohesive: 0.00ps; little cohesion: 0.33ps; moderate cohesion: 0.67ps; full cohesion: 1.00ps.						
I8. Water	%	Score as a function of the % of recycled water. 0-25%: 0.25ps.; 25-50%: 0.5ps.; 50-75%: 0.75ps.; >75%: 1.00ps.						
I9. Energy	MJ/m	400	57.9	24.5	24,5	1.00	3.00	DS
		800	906	73.32	350	0.95	1.95	DS
		1200	993	145	350	0.65	3.00	DS
		2000	3960	380	1800	1.00	3.00	DS
I10. Sensitivity	Points	Scores without environmental certification; 0.0ps. Score for each measurement of environmental commitment: 0.2ps. With ISO 14001: 1.0ps certification.						

Table 5. Requirement values for each alternative

D_n (mm)	Material	Functional	Economic	Environmental			Social
				Scenarios			
				A	B	C	
400	UC	0.68	0.92	0.64	0. 44	0.24	0.67
	PP	0.45	0.85	0.90	0.75	0.60	0.64
800	SBRC	0.69	0.83	0.98	0.78	0.58	0.59
	PVC	0.44	0.76	0.61	0.46	0.31	0.54
1200	SBRC	0.65	0.85	0.88	0.68	0.48	0.41
	PE	0.29	0.72	0.70	0.55	0.40	0.44
2000	SBRC	0.58	0.82	0.93	0.73	0.53	0.30
	PFRV	0.63	0.05	0.58	0.43	0.28	0.28

The results presented in **table 5** show that, for D_n equivalents: (1) the UC pipes and the SBRC pipes have higher scores for the functional requirement due to the greater added structural capacity of a flexible solution and because of their technical advantages in connection with the risk of failure and problems in the joints that is also lower in rigid piping. This difference increases with the diameter (except in the case of the PFRV pipes that present a higher index value); (2) at an economic level, they all present similar index values, except for the PFRV-2000 solution that is designed for flows under pressure; (3) with regard to the environmental requirement, the PP-400 pipes presented a better index value than the UC-400 pipes; however, the tendency was reversed for higher D_n and the SBRC pipes scored more favorably than the flexible solutions. These higher scores were in part due to the need for screened (selected) soil as a backfill for these flexible tubes with a wider diameter and to guarantee acceptable safety in compliance with the structural requirements (section 3.2), while the same natural soil may be reused as backfill for the SBRC pipes.

Table 6. Global sustainability index values for each alternative

D_n (mm)	Material	Scenario A	Scenario B	Scenario C
400	UC	0.75	0.68	0.61
	PP	0.78	0.73	0.68
800	SBRC	0.81	0.75	0.68
	PVC	0.63	0.58	0.53
1200	SBRC	0.74	0.67	0.61
	PE	0.60	0.55	0.50
2000	SBRC	0.72	0.65	0.58
	PFRV	0.34	0.29	0.24

The remaining indicators for the environmental criteria present practically equivalent values for all the alternatives under study. The PFRV-2000 are those that obtain a lower index value for the environmental requirement. It should, in addition, be underlined that the prioritization for the different alternatives remains the same, regardless of the scenario under analysis and that, in any case, if the environmental sensitivity of the manufacturing process increases, then the environmental score of the alternative also increases. Finally, (4), the rigid and plastic solutions present similar scores with regard to the social requirement, reducing the index value as the diameter of the pipes increase. It should be highlighted that the concrete pipes were given higher scores for contamination of the water table and vulnerability, while the flexible pipes had a better level of satisfaction in relation to accidents at work due to their lighter weight and, therefore, lower risk of accidents and personal injury.

In the light of the results presented in **table 6**, it may be concluded that both the UC and the PP pipes presented practically similar global sustainability indexes for D_n = 400, the latter gaining a slightly higher index value in all scenarios. On the contrary, the SBRC pipes gained a better index value for $D_n \geq 800$ mm in comparison with the flexible pipe alternatives with an equivalent D_n, because the former presented a global balance for all the requirements.

The results of this analysis were subsequently presented at the final technical seminar at which the technical experts in attendance confirmed the tendencies and the prioritization that had been obtained and, moreover, confirmed that it reflected the reality of their professional experience.

5. SENSITIVITY ANALYSIS

Table 7 presents the sustainability indexes of the eight alternatives. In addition to the 3 scenarios analyzed in the study case (case 1) described in section 3.2, four different extreme cases have been assessed. These additional cases focus on each of the four requirements by giving a weight of 70% to this main requirement and 10% to the other three requirements. These cases are: functional case (case 2); economic case (case 3); environmental case (case 4) and social case (case 5).

For the sake of the interpretation of the results and to facilitate the analysis of these, the results of the scenario B (normal environmental sensitivity of the production plant) are presented in **figure 1**.

The results gathered in **figure 1** highlight that:

Table 7. Sustainability indexes of the different cases considered in the sensitivity analysis

		Case 1 Study case			Case 2 Functional			Case 3 Economic			Case 4 Environmental			Case 5 Social		
	Scenario	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
D_n (mm)	Material															
400	UC	0,75	0,68	0,61	0,70	0,68	0,66	0,84	0,82	0,80	0,68	0,54	0,40	0,77	0,75	0,73
	PP	0,78	0,73	0,68	0,55	0,54	0,52	0,79	0,78	0,76	0,82	0,72	0,61	0,67	0,66	0,64
800	SBRC	0,81	0,75	0,68	0,72	0,70	0,68	0,81	0,79	0,77	0,90	0,76	0,62	0,77	0,75	0,73
	PVC	0,63	0,58	0,53	0,50	0,48	0,47	0,69	0,68	0,66	0,60	0,50	0,39	0,60	0,58	0,57
1200	SBRC	0,74	0,67	0,61	0,67	0,65	0,63	0,79	0,77	0,75	0,81	0,67	0,53	0,73	0,71	0,69
	PE	0,60	0,55	0,50	0,39	0,37	0,36	0,65	0,63	0,62	0,64	0,53	0,43	0,52	0,50	0,49
2000	SBRC	0,72	0,65	0,58	0,61	0,59	0,57	0,76	0,74	0,72	0,82	0,68	0,54	0,68	0,66	0,64
	PRFV	0,34	0,29	0,24	0,53	0,52	0,50	0,18	0,17	0,15	0,50	0,40	0,29	0,36	0,34	0,33

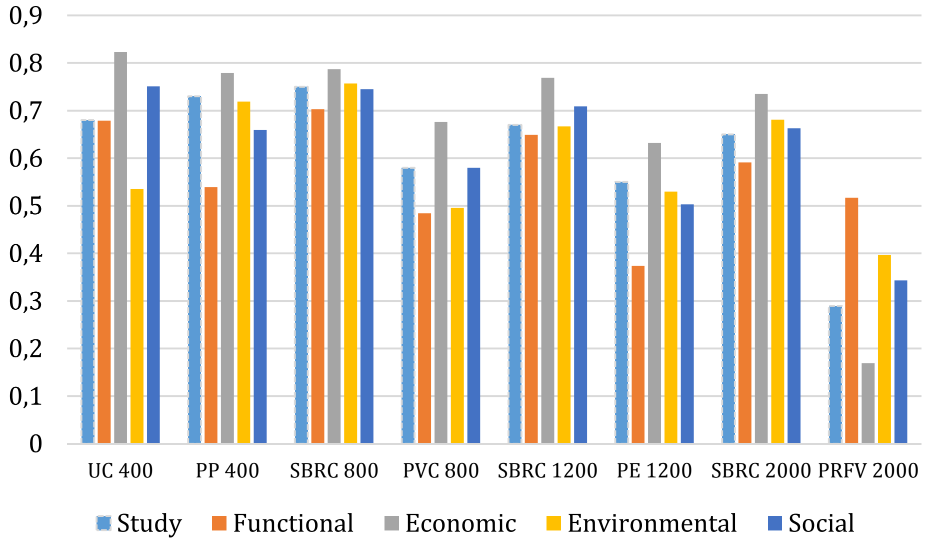

Figure 1. Sustainability indexes for Scenario B (average conditions). Sensitivity analysis

- UC–400 presents a greater sustainability index with respect to PP–400 in those cases for which the functional (0.68 for UC-400 and 0.54 for PP-400), the economic (0.82 for UC-400 and 0.78) or the social (0.75 for UC-400 and 0.66 for PP-400) requirements are emphasized. Contrarily, it could be observed that the relative difference between both pipes increase even more in the case 4 (environmental); PP-400 (0.72) presenting a sustainability index a 22.2% larger than that obtained for UC-400 (0.54).
- SBRC 800 and SBRC 1200 exhibit greater sustainability indexes in all the studied cases with regard the other alternatives studied (PVC 800 and PE 1200, respectively). Likewise, it could highlighted that the sustainability indexes of both SBRC 800 and SBRC 1200 are quite robust since the sensitiveness of these with respect the extreme weighting variation is low: 11.9% for SBRC 800 (0.79 for case 4 and 0.70 for case 3) and 18.4% for SBRC 1200 (0.77 for case 4 and 0.75 for case 3).
- SBRC-2000 performs far better in terms of sustainability in contrast with PRFV-2000 (from 14.3% for case 2, functional, to 335% for case 3, economic). However, as it was stated in section 3 and 4, this is mainly due to the

additional mechanical performance that PRFV-2000 (internal pressure strength capacity) which is not necessary for sewerage pipes.

5. Conclusions

A multi-criteria model based on the MIVES methodology has been developed for this study, which may be used to minimize subjectivity in the process of comparing and classifying pipe alternatives for sewerage networks. The model has enabled to evaluate the sustainability index of each alternative, through the value functions and the weights assigned to the different indicators, criteria and requirements of the decision tree. All the elements that constitute the model were established in the course of seminars at which experts in manufacturing, design and installation of sewerage pipes and networks participated alongside senior managers of decision bodies in the Spanish public administrations. The decision tree and its components were calibrated and oriented towards satisfying the information needs of public administration committees where the decisions are taken in relation to the sewerage networks.

The model has been used to evaluate the degree of sustainability of 8 piping alternatives, in which non-reinforced concrete piping (UC) and reinforced SBRC were used as representative of the segment of rigid pipes, as well as polypropylene (PP), polyethylene (PE), poly(vinyl chloride) (PVC) and glass-fiber reinforced polyester (PRFV) pipes from the market segment of flexible pipes. Likewise, nominal diameters of 400, 800, 1200 and 2000 mm were considered to cover the range of flows that are usually transported in urban and rural networks.

The specific conclusions obtained from this study are:

1. The proposed model constitutes an advance in terms of sustainability assessment since this guarantees great objectivity and clarity to the method. This gives greater legitimacy to the valuation of the model that virtually anyone could use to calculate the sustainability index. The results and conclusions of this study can serve to establish the foundations for subsequent analyses of other prefabricated products, as well as to support decisions taken within the public administrations.

2. The differences in terms of a sustainability index for the alternative materials with diameters of 400 mm (and applicable to lower diameters) were not significant. This fact is reflected in the market with an important penetration of plastic pipes in a segment that was previously monopolized by rigid concrete pipes. However, these differences increase with the diameter of the pipes; the difference in the sustainability index between the concrete and the plastic solutions being greater for the former. Finally, as the sensitivity analysis highlighted, these conclusions are robust and can be extended to other scenarios with different distribution of weights.

The proposed method may be used for the evaluation of piping that are laid in various environmental conditions, sensitivities and priorities, other than those considered in this study. The same requirements tree may be adapted for that purpose and the weights and value functions of the specific needs of the decision-makers may be calibrated. The authors especially consider that the organization of seminars of experts together with the use of the AHP method for the allocation of weights is a very appropriate and useful procedure for this process of adaptation, which serves to guarantee representativeness, coherence and objectivity in the decision-making process.

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