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Sustainability assessment of trenches including the new eco-trench: A multi-criteria decision-making tool

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Abstract

Narrow trenches are a common technique for the installation of utility pipelines of small diameter. The excavated soil is not always appropriate as landfill and, in those cases, an appropriate soil from somewhere else (ex. a borrow pit or another construction site) should be used instead (classical solution, CS). Another common solution is to use a controlled low-strength (cementitious) material (CLSM) as backfill instead of compacted soil. However, both solutions lead to increased raw material consumption, waste generation, need for transportation, and CO_2 emissions. In an attempt to address these issues, researchers developed an eco-trench (ECO) that reuses the excavated soil of narrow trenches to produce a controlled low-strength material to be used as landfill. Although technically viable, the sustainability of this solution versus the traditional solution has not been properly addressed. Hence, this paper aims to develop a method for the sustainability assessment of trenches. The Sustainability Index of Trenches (SIT), based on the MIVES decision-making method, enables the assessment and prioritisation of different types of trenches according to sustainability criteria. Criteria, indicators, weights and value functions were specifically defined based on seminars with experts in the field of utility services and construction. A case study was performed in which four types of trenches (CS, CS with recycling CS+R, CLSM and ECO) were assessed and prioritised according to SIT. ECO resulted in the most sustainable alternative with a SIT of 0.80 out of 1 followed by CS+R, CS and CLSM with SITs of 0.63, 0.40 and 0.38 respectively. The sensitivity analysis showed consistent results in different scenarios. These findings demonstrate the capability and reliability of SIT as a decision-making tool for the

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evaluation of the sustainability of different construction processes for trenches and the prioritisation of the most suitable solution for different situations.

Keywords: Trench; Eco-trench; Sustainability assessment; MIVES; Multi-Criteria Decision-Making.

1. INTRODUCTION

Trench construction entails affectations to urban mobility, noise and dust pollution; however, it has been traditionally regarded as a necessary evil to provide basic utility services such as drinking water, electricity and gas. Nowadays, as citizens are more aware of the environmental and social impacts, their demands for solutions with low economic, environmental and social impacts are increasing.

The use of narrow trenches to install flexible pipelines of small diameter is a common technique for the construction of utility services networks (Blanco et al., 2014) that generates very limited interference with other services or traffic during construction. After the trench is excavated, a backfill material is used to fill the void left behind as well as to provide the support for the pipe and the surface elements. Traditional trench reinstatement methods use common soils and manufactured unbound granular materials as backfill and two top layers, one of concrete and one of bituminous asphalt to restore the pavement surface. However, several common deficiencies may arise with this method. A poor selection of soils or inadequate compaction may lead to settlements and other problems during the service life of the conventional trench (e.g. critical load concentrations in the pipe and pavement subsidence). In this context, the reuse of extracted soil is limited due to the difficulties related to the proper selection and separation, as well as the risk of future problems. Overcoming these drawbacks and promote the reuse of extracted soil requires changing the typical philosophy behind the narrow trench system.

Alternatively, the backfill used in narrow trenches instead of compacted soil is a cementitious material (made of a binder, aggregates, water, and admixtures) known as controlled low-strength material (CLSM) (Alizadeh, 2018, 2019; Etxeberria et al., 2013; and Wu et al., 2016). This material is highly fluid to allow the filling of tight and restricted areas in which placing and compaction would be otherwise difficult, but not excessively fluid so that the material may remain in place in trenches with a slope. CLSM presents a compressive strength between 0.7 and 1.4 MPa, which represents a minimum strength to ensure the loads applied over the trench without achieving excessively high values that compromise re-excavation for the repair and maintenance of the installation.

However, both solutions, the conventional (Chen et al., 2018) and the CLSM trenches (Zhang et al., 2018; Pujadas et al. 2015; and Taha et al 2007), lead to a significant raw material consumption and CO_2 emissions associated with the materials transportation among other environmental, economic and social impacts (Petit-Boix et. al, 2016). Recently, Blanco et al. (2017) presented an alternative solution, which consists in reusing the excavated material and a finishing layer of expansive concrete. This solution, called eco-trench (ECO), consists in re-using the trench arisings as the main backfill and in finishing the trench with a top layer of expansive concrete. The expansive concrete contains a calcium oxide admixture that generates a volumetric expansion during early ages. Given its properties, this admixture has been commonly used to compensate shrinkage.

In the case of trenches, the purpose of generating a volumetric expansion is not solely intended to compensate shrinkage but also to generate internal stresses due to the confinement of the concrete. This phenomenon may favour the transmission of stresses from traffic loads to the surrounding soil, thus relieving the stresses on the backfill material and pipe. Consequently, the restrictions related to the backfill selection are eliminated, making the reuse of the soil possible without compromising the speed of the construction process or the performance of the pavement. Moreover, this solution simplifies the execution by avoiding the final layer of asphalt (no overlaps are required) and the logistics while contributing to reducing the time of construction.

Sustainability has become a paramount factor in design and construction guidelines (Gobierno de España, 2008); hence, new construction methods should not be assessed only in terms of technical feasibility but also in terms of sustainability. Sustainability studies should consider the inseparable nature of environmental, social and economic aspects of development activities (Huang et al. 2016; United Nations, 2013; and Veldhuizen et al., 2015). Sustainability index representations have developed in various industries and for different purposes (Chang et al., 2018). However, the assessment of social factors has not been yet consolidated in urban studies. As an example, methods promoted by construction companies usually focus on economic aspects.

Meanwhile, public administrations or non-governmental organisations tend to reinforce environmental aspects. Life Cycle Analysis (LCA) is one of the most popular environmental methods (Bilec et al., 2006; Borghi et al. 2018; Chang et al., 2013; Jang et al. 2015; and Sharrard et al., 2008), in which environmental impacts, positive and negative, are assessed throughout the life cycle of the new construction. Life Cycle Costing (LCC), which arose as a derivation of LCA methods, analyses economic factors in the assessment of sustainability.

Beyond these tools, there are Multi-Criteria Decision-Making (MCDM) models, which are essential for assessing different aspects of projects including sustainability (da S Trentin et al., 2019; Huang et al., 2011). In the field of narrow trenches and to the best of the authors' knowledge, there are no models to assess sustainability, considering their environmental, social, and economic impacts. For this reason, the authors have developed the Sustainability Index of Trenches (SIT), which assesses the sustainability of any trenches to accommodate service pipes in urban soils.

Different MCDM tools can be used to define sustainability indexes. The most well known are ELECTRE (Benayoun et al., 1966), Analytical Hierarchy Process (Saaty, 1980), TOPSIS (Hwang and Yoon, 1981), PROMETHEE (Brans and Vincke, 1985) and VIKOR (Opriovic, 1998). However, for defining the SIT, the authors selected MIVES (from the Spanish 'Modelo Integrado de Valor para una Evaluación Sostenible' [Integrated Value Model for Sustainability Assessment]), which was originally developed for the assessment of sustainability in construction (Aguado et al., 2012; Jato-Espino et al., 2014; Pardo and Aguado, 2016; Pujadas et al., 2018; Roigé et al. 2019; and San Jose and Garrucho, 2010). MIVES incorporates the Analytical Hierarchy Process for the assignment of weights to all the components of the tree and the value functions (Alarcon et al. 2011) that transform the different units of the indicators into a dimensionless value or satisfaction measure that ranges from 0 to 1. According to da S Trentin et al., (2019), MIVES has gained prominence in sustainability-related studies because its features make this method effectively support decision-makers in the selection of sustainable alternatives. The results in the assessment of alternatives are readily interpretable, making it possible to perform comparative studies and derive conclusions regarding the improvement of sustainability in construction projects. This method has already been successfully applied in several homogenous and heterogeneous decisions (Aguado et al., 2017; de la Fuente et al., 2017, 2019; Pardo-Bosch and Aguado, 2015; Pujadas et al., 2017; and Oses et al., 2017).

The remaining of the paper is structured in four more sections. Section 2 develops the SIT based on MIVES, including the value tree, weights, indicators and value functions. Section 3 provides a case study in which the sustainability of four types of trenches is assessed using the SIT. Section 4 deals with a sensitivity analysis; and, finally, section 5 focuses on the conclusions of the research.

2. METHODS: SUSTAINABILITY INDEX FOR TRENCHES (SIT)

Decision-making is becoming more complex as more criteria, points of view and stakeholders are considered. Multi-criteria decision-making (MCDM) methods can help with the decision-making process so that it is structured, objective and straightforward. MCDM methods are being increasingly applied for infrastructure management (Kabir et al., 2013) with successful experiences in a wide range of topics such as water-heating systems (Casanovas-Rubio and Armengou, 2018), urban pavements (Pujadas et al. 2018) and infrastructure investments (Pujadas et al. 2017).

Among the MCDM available, SIT was defined according to the MIVES method. In subsequent sections, the definition and development of this sustainability index are described in detail.

2.1. Requirement tree and weights

The requirements tree defined for SIT includes the three pillars of sustainability: economy, environment and society (U.N., 2013), as shown in Fig. 1. These requirements are divided into five criteria that eventually lead to eight indicators, which are the only concepts of the tree that are evaluated either through qualitative or quantitative variables, with different units and scales (Alarcon et al., 2011). The tree was defined using seminars with 6 experts, which, according to Daim et al. (2012), is the number needed to “stabilise” the AHP matrix and thus provide credible and reliable results. The participants were selected based on their background and experience: 4 work in an international utility service company (2 technicians and 2 C-level profiles, all with an industrial engineering background), and the other 2 are civil engineers from a publicly owned company responsible for the coordination of construction work of services in the public space in Spain.

The *economic requirement* assesses the use of the economic resources of the entity that finances the construction involving trenches. It contains a single criterion, the investment (see Fig.1). The *environmental requirement* takes into account the degree in which the different alternatives contribute to the conservation of the natural and built environment. It consists of three criteria: resources, energy, and emissions and waste, and five indicators. The *social requirement* accounts for the social impact within the construction site, i.e. the occupational risks, and the external impact, i.e. the inconveniences caused to the citizens in the surroundings. The latter includes the public space occupation and the noise and dust generation.

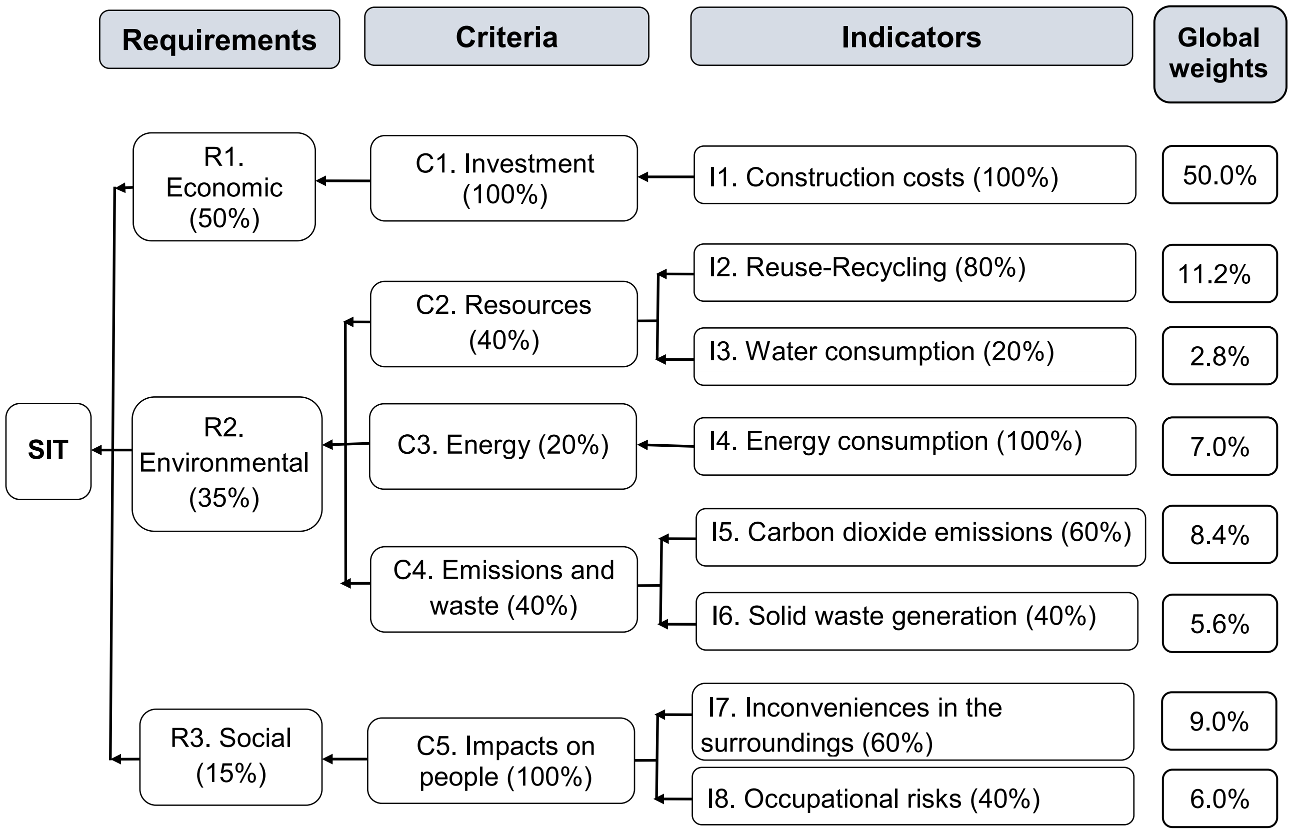

Fig. 1. Requirement tree for the SIT and weights

The local and global weights that represent the relative importance of the requirements, criteria, and indicators are presented in Fig. 1. The local weights were assigned in the seminars by the experts according to their knowledge, expertise and preferences. The global weights of the indicators were calculated by multiplying the local weight of the indicator by the local weights of the corresponding criterion and requirement according to the MIVES method. Notice that these weights can change depending on the user or decision-maker; however, the values herein presented can be taken as a benchmark. The construction costs are the indicator with the highest importance: 50% of the total, followed by the environmental requirement, with a weight of 35% and, finally, the social requirement with a weight of 15%. Within the environmental requirement, the criteria resource consumption and emissions and waste are considered to have the same importance (40% each) and double of the energy (20%). The most important indicator within the environmental requirement is reuse-recycling, with 11.2% of the total importance (global weight).

The use of recycled and reused materials is beneficial to the environment because it reduces the consumption of new materials, as well as the energy and water consumption (Sepehri and Sarrafzadeh, 2018) necessary for its production. The carbon dioxide emissions indicator was also considered relevant (8.4%) by the experts due to their effects on climate change and the existence of the greenhouse gas market. The least important indicator according to the experts, i.e. water consumption, has a global weight of 2.8%, which means that any other possible indicators that were not included in the requirement tree would have lower importance. Within the social requirement, the inconveniences caused in the surroundings were considered more important than the occupational risks when choosing the best type of trench.

2.2. Indicators and value functions

In this section, each of the indicators and value functions defined for SIT is described in detail.

2.2.1. Construction costs (I_1)

The indicator construction costs (I_1) evaluates the costs due to the construction work of a trench per metre of the trench (in €/m). It is assumed that the signalling, fencing, lighting, testing and administrative costs are the same for all the alternatives and, therefore, not included in the indicator. Only the construction stage that varies according to the trench alternative, i.e., the construction itself, is considered. Regarding the value function for the construction costs indicator, the minimum cost obtains the maximum value. Therefore, the value function is decreasing and the sigmoid function (see Fig. 2) favours the alternatives with a lower cost and penalises those with a higher cost.

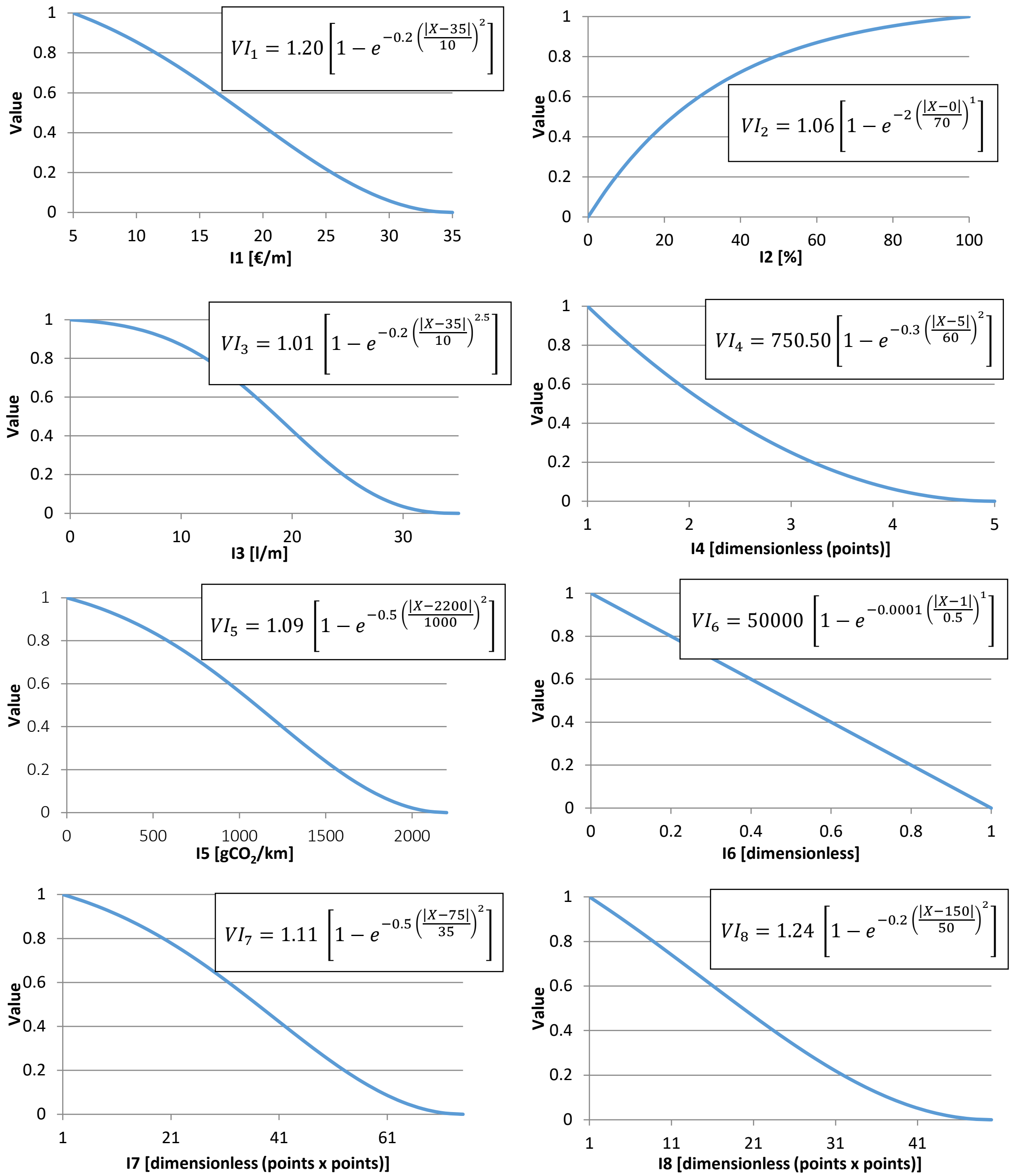

Fig. 2. Value functions

2.2.2. Reuse-recycling (I_2)

According to the service companies that participated in the seminars, traditionally, the material excavated from the trenches was disposed in landfills, and the trenches were filled with new granular material, a concrete layer, and an asphalt layer at the top. A more sustainable alternative is to fill part of the trench with the excavated material provided that it meets the technical requirements. Although less common, it is also possible to fill the trench with another type of recycled material. The use of concrete and asphalt made with recycled aggregates is also possible. The reuse-recycling indicator (I_2) evaluates the quantity of these three types of reused and recycled materials that can be used in trenches (Equation (1)).

$$I_2 = w_1 \cdot ExM + w_2 \cdot RAg + w_3 \cdot ORM \qquad [\%] \tag{1}$$

where: ExM, RAg, and ORM are, respectively, the percentages of the volume of the trench filled with material excavated from the trench itself, concrete or asphalt with recycled aggregates, and other recycled or reused materials that do not come from the trench under construction.

w_1, w_2, and w_3 are weighting factors that fulfil $w_1 + w_2 + w_3 = 1$. For the present analysis, the following weights were taken: $w_1 = 0.7, w_2 = 0.15$, and $w_3 = 0.15$. These weights represent the relative importance assigned to the use of each recycled material, according to the experts in the seminars.

The higher the use of recycled and reused materials, the higher the value of the alternative. Thus, the selected value function has an increasing tendency (see Fig. 2). A concave shape was chosen to favour the alternatives that reduce the consumption of new materials.

2.2.3. Water consumption (I_3)

The water consumption indicator (I_3) evaluates the amount of consumed water according to the technical trench alternative. It considers the water consumed during the material production and the construction work of the trench (Equation (2)). The indicator includes the most relevant consumptions that discriminate between trenches: the water for the concrete/mortar production (WaC), Equation (3), and soil compaction (WaS), Equation (4). The amount of water necessary to correctly compact the soil can be estimated as a ratio of the weight of the soil.

$$I_3 = WaC + WaS \qquad \text{[in l/m]} \qquad (2)$$

$$WaC = S_C \cdot W_C \qquad \text{[in l/m]} \qquad (3)$$

$$WaS = \frac{S_S \cdot D_S \cdot \alpha}{D_W} = 0.10 \cdot S_S \cdot D_S \qquad \text{[in l/m]} \qquad (4)$$

where: S_C is the section of the trench filled with concrete [m^2].

W_C is the volume of water per unit volume of concrete [l/m^3].

S_S is the section of the trench filled with soil [m^2].

D_S is the apparent density of the soil [kg of soil/m^3].

α is the ratio weight of water/weight of soil. According to Gutiérrez and Pereira (2006), it can be estimated as a 0.10 [kg of water/kg of soil].

D_W is the apparent density of the water [kg of water/l]. The value of 1kg/l is taken.

The higher the water consumption, the lower the value of the alternative, which is reflected by a decreasing value function, as presented in Fig. 2. The sigmoid function selected for this indicator favours alternatives with low water consumption and penalises those with higher consumption.

2.2.4. Energy consumption (I_4)

The energy consumption of the construction of a trench can be divided into three stages: manufacture and transportation of construction materials, and construction work (Casanovas-Rubio and Ramos, 2017). Although it is possible to quantify the energy consumption in these stages, a lot of data is necessary, and it is time-consuming. An evaluation using attributes is proposed to facilitate the application of the proposed tool when choosing the most sustainable trench.

The assessment of energy consumption due to the manufacture of construction materials (CMM) is made according to Equation (5).

$$CMM = \sum_{i=1}^{n} \frac{M_i}{100} \cdot P_i \qquad \text{[dimensionless (points)]} \qquad (5)$$

where: i is each one of the materials of the trench.

n is the total number of materials used in the trench.

M_i is the percentage of the material i used in the trench [%].

P_i are the points corresponding to the material i (Table 1).

Table 1. Points assigned to the different levels of energy consumption for the three stages considered

Levels of energy consumption			Attribute	Points P_i and P_j
Manufacture of materials	**Transportation of materials**	**Construction**		
New material (concrete and asphalt plant aggregate)	Material from a recycling plant or transported to a recycling plant	Mechanical implementation in more than one layer or stages (soil compaction)	High	5
Recycled material (treated in a recycling plant or the construction site)	Material from a concrete or asphalt plant or transported to a landfill	Simple mechanical implementation (one single layer)	Medium	3
Reused material (untreated, from the excavation of the trench or another construction work)	Used in the same construction site	No need for mechanical implementation	Low	1

The energy consumption due to the transportation of construction materials (CTM) is assessed according to Equation (6).

$$CTM = \frac{1}{2}\left(\sum_{i=1}^{3} \frac{M_i}{100} \cdot P_i + \sum_{j=1}^{3} \frac{N_j}{100} \cdot P_j\right) \qquad \text{[dimensionless (points)]} \qquad (6)$$

where: i represents each one of the three possible origins of the materials (recycling plant, concrete or asphalt plant, and construction site).

M_i is the percentage of materials with the origin i used in the trench [%].

P_i are the points corresponding to the origin i (Table 1) [dimensionless]. It is assumed that the trench is constructed in an urban area and that the recycling plants are further away than the concrete plants, asphalt plants or landfill. In other cases, the points that best suit the real situations should be assigned.

j represents each one of the three possible destinations of the materials (recycling plant, landfill, and construction site).

N_j is the percentage of the materials with the destination j produced in the trench [%].

P_j are the points corresponding to the destination j (Table 1) [dimensionless].

The assessment of the energy consumption due to the construction work (CCW) is directly the points corresponding to the type of construction process P_i, as indicated in Table 1.

Finally, the indicator of energy consumption (I_4) is defined according to Equation (7).

$$I_4 = w_4 \cdot CMM + w_5 \cdot CTM + w_6 \cdot CCW \qquad \text{[dimensionless (points)]} \qquad (7)$$

where: $w_4 + w_5 + w_6 = 1$. Initially, the values considered for the ponderation are $w_4 = 0.3$, $w_5 = 0.5$, and $w_6 = 0.2$. These weighting factors represent the relative importance that the experts on the seminars assigned to the minimisation of the energy consumption in the different stages.

The minimum energy consumption provides maximum satisfaction, as reflected in Fig. 2. The convex shape of the function penalises high-energy consumptions.

2.2.5. Carbon dioxide emissions (I_5)

Based on Highway Authorities and Utilities Committee (2007) it is assumed that the stage that discriminates the most between the different types of trenches regarding the CO_2 emissions is the transportation of construction materials and this is the stage considered in the method. Equation (8) corresponds to the indicator of carbon dioxide emissions (I_5), which is measured in a mass of CO_2 emissions per unit length of the trench.

$$I_5 = \frac{1}{l} \cdot \sum_{j=1}^{3} \sum_{i=1}^{m} E_{ij} \cdot d_{ij} \cdot n_i \qquad [gCO_2/km] \qquad (8)$$

where: i is a vehicle that transports construction material to the construction site or solid waste from the construction site to elsewhere (e.g. recycling plant or landfill) (Table 2).

j is each type of road (Table 2).

l is the length of the trench [km].

E_{ij} is the emission of vehicle i when it circulates in the type of road j. The values from Table 2 can be used [gCO_2/km].

d_{ij} is the round-trip distance travelled by the vehicle i in the road j [km]. The trips to be considered are to transport concrete from the concrete plant with a mixer truck or asphalt from the asphalt plant (6 m^3 of capacity), soil (9 m^3), solid waste to the landfill or to the recycling plant (9 m^3).

n_i are the number of trips of the vehicle i

The value of the alternatives decreases with the increase of greenhouse gas emissions. Therefore, a decreasing value sigmoid function was chosen (Fig. 2), which favours alternatives with low CO_2 emissions and penalises those with high emissions.

Table 2. CO_2 emissions according to the type of vehicle and road (Oficina Catalana pel Canvi Climàtic, 2013)

Vehicle			Emissions [gCO_2/km]		
			Urban	**Rural**	**Interurban**
Diesel lorry	Rigid	≤14t	788.53	397.25	410.38
		>14t	1629.90	487.52	470.09
	Articulated	≤34 t	1484.79	573.59	527.76
		>34 t	2147.16	666.35	590.14
Light	Petrol	-	391.20	210.84	213.71
	Diesel	-	307.69	194.48	268.78

2.2.6. Solid waste generation (I_6)

This indicator evaluates the degree in which the materials generated in the construction are reused or recycled either in the same construction or in other places/applications instead of being sent to a landfill as waste. The indicator of solid waste generation was defined as presented in Equation (9).

$$I_6 = 1 - \left(\frac{RcM + RuM}{100}\right) \quad \text{[dimensionless]} \quad (9)$$

where: RcM and RuM are the percentages of the material generated in the construction that is going to be recycled and to be reused, respectively, in the construction site or elsewhere [%].

The indicator represents the amount of solid waste sent to a landfill. Hence, the higher the solid waste, the lower the score of the alternative. Accordingly, the value function for this indicator was defined as a decreasing linear function (Fig. 2).

2.2.7. Inconveniences in the surroundings (I_7)

This indicator evaluates the inconveniences caused to the neighbours by the construction work depending on the type of trench. It considers the occupation of the public space (OPS), noise emission (NE), dust emission (DE) and duration of the impact (t). The indicator inconvenience in the surroundings (I_7) is defined as presented in Equation (10). The number of people suffering the inconveniences is not included because it does not discriminate between types of trenches (it is assumed that all the trenches compared are in the same location).

$$I_7 = OPS \cdot t + \left((NE_{Ex} + DE_{Ex}) \cdot t_{Ex} + (NE_{St} + DE_{St}) \cdot t + (NE_{Fill} + DE_{Fill}) \cdot t_{FF} + (NE_{SuF} + DE_{SuF}) \cdot t_{FF}\right)\frac{1}{4} \quad \text{[dimensionless (points x points)]} \quad (10)$$

The inconvenience of not being able to occupy public space is considered in OPS and qualitatively evaluated according to Table 3.

Table 3. Ratings of the impacts due to the occupation of the public space (OPS)

Description	Attribute	Points
The road traffic cannot circulate in the street with the trench. Pedestrians have serious difficulties in accessing their houses or stores.	Total	5
The road traffic cannot circulate, but pedestrians do not have serious difficulties in accessing their houses and stores	General	4
The road traffic circulates with restrictions, and there is a partial impact on pedestrians	Medium	3
There is no impact on the road traffic and the impact on pedestrians is very mild	Local	2
The impact is almost inexistent	Very local	1

The NE and DE are produced in different activities of the construction work of the trench: excavation (NE_{Ex}, DE_{Ex}), stockpile and preparation of the filling material (NE_{St}, NE_{St}), filling (NE_{Fill}, NE_{Fill}), and surface finishing (NE_{SuF}, NE_{SuF}). NE and DE are evaluated according to the levels in Table 4.

Table 4. Ratings of the noise (NE) and dust (DE) emissions

Level of the inconvenience	Points [dimensionless]
Highly remarkable	5
Medium	3

Almost inexistent	1

The different stages that cause the previous inconveniences have different durations according to the type of trench and are evaluated according to Table 5. t_{Ex} and t_{FF} correspond to the evaluation of the duration of the excavation and of the filling and finishing, respectively.

Table 5. Ratings of the duration of the different stages that cause inconveniences

Stage	Activity	Points [dimensionless]
Excavation (t_{Ex})	Manual	5
	Conventional machinery	3
	Trencher	1
Filling and finishing (t_{FF})	More than one material plus asphalt layer	5
	More than one material without asphalt layer	3
	a single material (concrete)	1

The duration of the impact of the whole construction of the trench (t) is evaluated according to Equation (11).

$$t = \frac{1}{2} \cdot (t_{Ex} + t_{FF}) \quad \text{[dimensionless (points)]} \quad (11)$$

The less social inconveniences an alternative causes, the more value the alternative provides. The decreasing sigmoid function shown in Fig. 2 favours alternatives with least inconveniences and penalises those with the highest.

2.2.8. Occupational risks (I_8)

This indicator evaluates the degree of risk to which the construction workers are exposed depending on the construction process and type of trench. Some activities imply a higher degree of risk even though all the appropriate preventive measure are applied. The occupational risks indicator (I_8) is presented in Equation (12). A more elaborated way of assessing occupational risks is defined in Casanovas et al. (2014).

$$I_8 = \sum_{i=1}^{n} Risk\ of\ activity_i = \sum_{i=1}^{n} P_i \times C_i \quad \text{[dimensionless (points)]} \quad (12)$$

where: i represents each one of the activities carried out in the construction.

P_i is the points corresponding to a level of probability of having an accident during the activity i and is evaluated in Table 6 [dimensionless].

Table 6. Ratings of probability and consequences

Levels of probability and severity of the consequence	**Points**
High	5
Medium	3
Low	1

C_i is the points corresponding to the level of severity of the most probable consequence if the accident occurs and is evaluated in Table 6 [dimensionless]. The number of workers and the duration of the activity are implicitly considered in the evaluation of the probability.

The proposed value function is a decreasing sigmoid function so that the maximum value is obtained for the minimum occupational risk evaluation (Fig. 2). The aim is to favour alternatives with the lowest labour risks.

Although the resulting value function is different for each indicator, all of them correspond to the same general formulation, which facilitates the practical implementation of MIVES. All the value functions have been defined in the seminars with the experts by consensus.

3. CASE STUDY

3.1. Description

The objective of this section is to present a practical application of the decision-making method to the four types of trenches presented in Fig. 3.

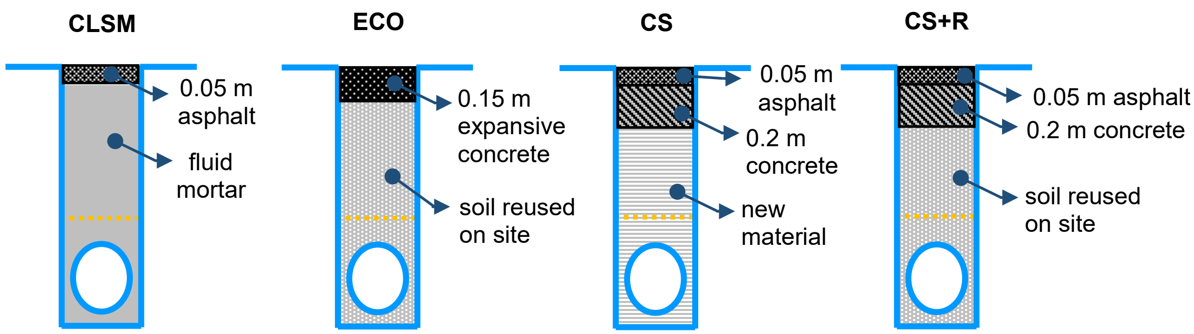

Fig. 3. Different types of trenches

1. Controlled low-strength material (CLSM): The filling consists of a fluid mortar of low compressive strength (around 2 MPa) for the whole height of the trench (Blanco et, al 2014; and Pujadas et al. 2015). Later, the 0.05 m of the top are removed by a milling cutter including an extra width of 0.20 m at each side of the trench for overlapping with the rest of the pavement. Finally, an asphalt layer of 0.05 m thick as wearing course is placed.

2. Eco-trench (ECO): The excavated soil is reused until 0.15 m before the top which is filled with a slightly expansive concrete that incorporates a black pigment in the surface to obtain the same colour as the rest of the asphalt pavement. There is no need (neither for aesthetic or technical reasons) for an asphalt layer or overlapping due to the expansive properties of the concrete and pigments used. More details on the ECO can be found in Blanco et al. (2017).

3. Classical solution (CS): The excavated soil is transported to a landfill or recycling plant. New material is used as a filling and, then, a concrete layer until the top. Later, the 0.05 m of the top are removed by a milling cutter including an extra width of 0.20 m at each side of the trench for overlapping with the rest of the pavement. Finally, an asphalt layer of 0.05 m thick as wearing course is placed.

4. Classical solution with recycling (CS+R): In this solution, the extracted soil is reused on site.

All of them are located in an asphalt carriageway and have a width of 0.15 m and a depth of 0.75 m and a nominal diameter of the tube of 110 mm. The trenches are excavated using a trencher, the adequate excavation method for a trench of these dimensions.

3.2. Input data

Some additional considerations for the calculation of I_1, are commented next. The construction costs of the four trenching alternatives were calculated using the prices of the Bedec database of the Catalan Institute of Construction Technology (ITeC). The used prices correspond to the 01/01/2017 database for Spain and include the direct costs (labour, materials, plant and auxiliary costs). Indirect costs, i.e. costs that are not directly attributable to a specific construction unit such as indirect labour, temporary constructions and facilities are not included. Overheads and industrial profit are neither included. The following stages were considered in the calculation of the costs:

1. Trench excavation with trencher for the different hypothesis of ground: soft and solid soil, and soft, medium, and hard rock. These are the same for the four alternatives.
2. Load and transport of the waste to an authorised landfill, including the price charged by the landfill. For the CLSM and CS, this corresponds to the whole volume excavated including the bulking, whereas for the ECO and CS+R, to a 35% of that volume.
3. Compaction of the soil for the ECO, CS and CS+R considering different types of soil: selected, suitable, and tolerable. Borrowed material is needed for the CS and mortar for the CLSM.
4. The corresponding surface finishing was considered for each alternative, as explained in section 3.1 and Fig. 3.
5. The cost of the service pipes was not included in any of the alternatives.

Other data necessary to calculate the indicators of the economic, environmental and social requirements for the four alternatives are presented in Table 7.

Table 7. Parameters of each alternative

Indicator	Parameter		CLSM	ECO	CS	CS+R
	Economic requirement					
I_1	Performance [m/day]		140	120	120	120
	Environmental requirement					
I_2	Material that goes to landfill [%]		100	35	100	35
	Material that is recycled [%]		0	65	0	65
	Concrete or asphalt with recycled aggregates [%]		0			
	Other recycled or reused materials that do not come from the trench itself [%]		0			
I_3	Trench section [m^2]		0.1125			
	Concrete filling [%]		90	20	30	30
	Amount of water [l/m^3]		285	155	155	155
	Soil filling [%]		0	70	60	60
	Soil density (D_S) [kg/m^3]		1500			
I_4	New material [%]		100	30	100	35
	Recycled material [%]		0			
	Reused material [%]		0	70	0	65
	New material from a concrete or asphalt plant [%]		100	30	100	35
	Material from a recycling plant [%]		0			
	Material from the same construction site [%]		0	70	0	65
	Material to a landfill [%]		100	35	100	35
	Material used in the same construction site [%]		0	64	0	65
	Material to a recycling plant [%]		0			
	Routes		interurban			
	Lorries for the transport of the concrete and asphalt		<14 t			
	Lorries for the transport of the rest of the materials		>14 t			
I_5	Trips of the concrete mixer [no.]		85	20	30	30
	Travel distance of the concrete [km/trip]		80			
	Trips to the landfill [no.]		60	20	60	25
	Travel distance to the landfill [km/trip]		140			
	Trips to the recycling plant [no.]		0			
	Travel distance to the recycling plant [km/trip]		40			
	Trips to bring the aggregates [no.]		0	5	35	0
	Travel distance of the aggregates [km/trip]		50			
I_6	Solid waste that is going to be reused (*RuM*) [%]		10	65	10	65
	Solid waste that is going to be recycled (*RcM*) [%]		10			
	Social requirement					
I_7	Duration of the excavation (t_{Ex})		1			
	Duration of the filling and finishing (t_{FF})		5	3	5	5
	Occupation of the public space (OPS)		2			
	Dust during the trench excavation (DE_{Ex})		3			
	Dust during the stockpile and preparation of the filling material (DE_{St})		1	5	1	5
	Dust during the filling of the trench (DE_{Fill})		3			
	Dust during surface finishing (DE_{SuF})		1	3	1	1
	Noise during the trench excavation (NE_{Ex})		3			
	Noise during the stockpile and preparation of the filling material (NE_{St})		1	5	1	5
	Noise during the filling of the trench (NE_{Fill})		1	3	3	3
	Noise during surface finishing (NE_{SuF})		3	1	3	3
I_8	Transport outside the construction site	P_i x C_i	5x5	1x5	5x5	3x5
	Work with heavy equipment or heavy-goods vehicle		1x3	3x3	5x3	5x3
	Mechanical load handling and earthmoving		3x3	5x3	5x3	5x3
	Manual load handling		1x1			
	Work with light equipment		1x1			
	Handling of special products		3x1	3x3	1x3	1x3

The performance of the CLSM is higher than the rest of the trenches mainly because soil compaction is not required. Although some of the parameters are null for the four alternatives, e.g. “material to a recycling plant”, the parameter is still relevant and considered because in future studies with other alternatives could take different values.

3.3. Results and discussion

Table 8 presents the results of the indicators calculated for the four trench alternatives considered in the study.

Table 8. Results of the indicators for the four trench alternatives

	Indicator		CLSM	ECO	CS	CS+R
I_1	Construction costs [€/m]		19.39	7.78	19.09	15.42
I_2	Reuse-recycling [%]		0.00	45.50	0.00	45.50
I_3	Water consumption [l/m]	WaC	28.86	3.48	5.23	5.23
		WaS	0	11.81	10.12	10.12
		Total	28.86	15.30	15.36	15.36
I_4	Energy consumption [dimensionless (points)]	Manufacture of construction materials (CMM)	5.00	2.20	5.00	2.40
		Transportation of construction materials and waste (CTM)	3.00	1.65	3.00	1.70
		Construction work (CCW)	3.00	3.00	5.00	5.00
		Total	3.60	2.09	4.00	2.57
I_5	Carbon dioxide emissions [gCO_2/km]		1348	418	1151	526
I_6	Solid waste generation [dimensionless]		0.80	0.25	0.80	0.25
I_7	Inconveniences in the surroundings [dimensionless (points x points)]		19.00	18.00	21.50	27.50
I_8	Occupational risks [dimensionless (points x points)]		42.00	40.00	60.00	50.00

The resulting costs (I_1) were calculated as the average of the cost of the different types of excavated and compacted soils. The highest costs correspond to the CLSM and CS trenches, the two alternatives that do not reuse the soil on site, which increases the costs due to the borrowing and transportation of materials, transportation of waste, and landfill costs. The CS+R is cheaper than the CS because it reuses the material on site. The ECO has the lowest cost, as it reuses the material on site and is the only alternative that does not need the milling and asphalt layer operations.

Regarding the environmental indicators, the ECO and CS+R are the two alternatives with a higher percentage in the reuse-recycling indicator (I_2). The CLSM has the highest water consumption (I_3) between the four alternatives due to the production of the controlled low-strength material. The other three trenches (ECO, CS and CS+R) have a considerably lower water consumption, which is mainly due to the soil compaction (77%, 65% and 65%, respectively).

The ECO and CS+R are the alternatives with the lowest points in the energy consumption in the manufacture of construction materials as well as in the transportation of construction materials and waste because they reuse a great number of materials. The CS and CS+R have more points in energy consumption in the construction work than the ECO and CLSM because they have more layers and mechanical implementations. The highest points in the total energy consumption indicator (I_4) correspond to the CS and the lowest to the ECO.

The results of the CO_2 emissions indicator (I_5) reflect material transportation. The highest emissions correspond to CLSM and CS as expected, due to the transportation of material and waste. The last environmental indicator, the solid waste generation (I_6), is the ratio of the material that is not going to be reused or recycled. The CLSM and CS obtain the highest results.

Regarding the social indicators, the ECO is the trench that causes the lowest inconveniences in the surroundings (I_7), closely followed by the CLSM. It is also the alternative with the lowest occupational risks (I_8), closely followed by the CLSM.

Once the indicators have been calculated for the four studied alternatives, the next step in MIVES is to calculate the value or satisfaction provided by each alternative for each indicator using the value functions presented in Fig. 2. These values (prior to being multiplied by the weights) are presented in Table 9 for each indicator. Finally, the total value of each alternative (SIT) is calculated as the weighted sum of values for each indicator, as shown in Table 9. Notice that the values of SIT range from 0 to 1. Fig. 4 presents the results with the contribution of each requirement.

Table 9. Value for each indicator and type of trench and SIT

Indicator		Global weight	Value			
			CLSM	ECO	CS	CS+R
I_1	Construction costs	50.0	0.46	0.93	0.48	0.64
I_2	Reuse-recycling	11.2	0.00	0.77	0.00	0.77
I_3	Water consumption	2.8	0.06	0.67	0.67	0.67
I_4	Energy consumption	7.0	0.12	0.53	0.06	0.37
I_5	Carbon dioxide emissions	8.4	0.33	0.87	0.46	0.83
I_6	Solid waste generation	5.6	0.20	0.75	0.20	0.75
I_7	Inconveniences in the surroundings	9.0	0.81	0.82	0.77	0.67
I_8	Occupational risks	6.0	0.75	0.77	0.59	0.68
SIT		**100.0**	**0.38**	**0.80**	**0.40**	**0.63**

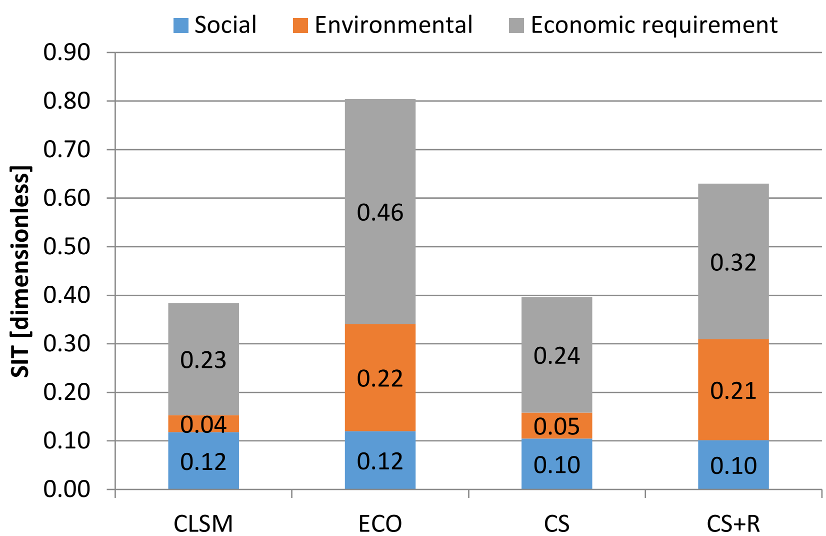

Fig. 4. SIT for each alternative

According to the resulting SIT, the best alternative is the ECO followed by the CS+R and, lastly, the CS and CLSM almost with the same SIT. The ECO and CS+R are the best alternatives because they minimise the need for new material, transport and waste disposal, which reduces the environmental impact and costs. The difference between the ECO and CS+R solutions is mainly due to the milling and the asphalt layer in the CS+R, as it generates higher inconveniences in the surroundings and has a higher cost. The ECO is the best alternative regarding the economic requirement, the best and very closely followed by the CS+R regarding the environmental requirement, and the best together with the CLSM regarding the social requirement.

4. SENSITIVITY ANALYSIS

The consistency of SIT was evaluated through sensitivity analysis by modifying the weight of the requirements. Table 10 presents the original weights, the weights in three different scenarios, and the resulting SIT for the four types of trenches. Scenario 1 corresponds to equal distribution of weights among the three requirements. In scenario 2, the environmental and social requirements have higher weights (and equal) than the economic requirement. In scenario 3, the environmental requirement is assigned the highest weight, followed by the social and economic requirements.

Table 10. Sensitivity analysis and results

Weight set	Local weigh of the requirement [%]			SIT			
	Economic	Environmental	Social	CLSM	ECO	CS	CS+R
Original	50.0	35.0	15.0	0.38	0.80	0.40	0.63
Scenario 1	33.3	33.3	33.3	0.45	0.79	0.44	0.64
Scenario 2	20.0	40.0	40.0	0.45	0.76	0.44	0.64
Scenario 3	20.0	50.0	30.0	0.38	0.74	0.38	0.63

Fig. 5 represents the resulting SIT for the four alternatives in the three different scenarios. The ECO is the best alternative and the CS+R the second best for the four sets of weights (the original and the three scenarios). The CLSM and CS have very similar values for the four weight sets.

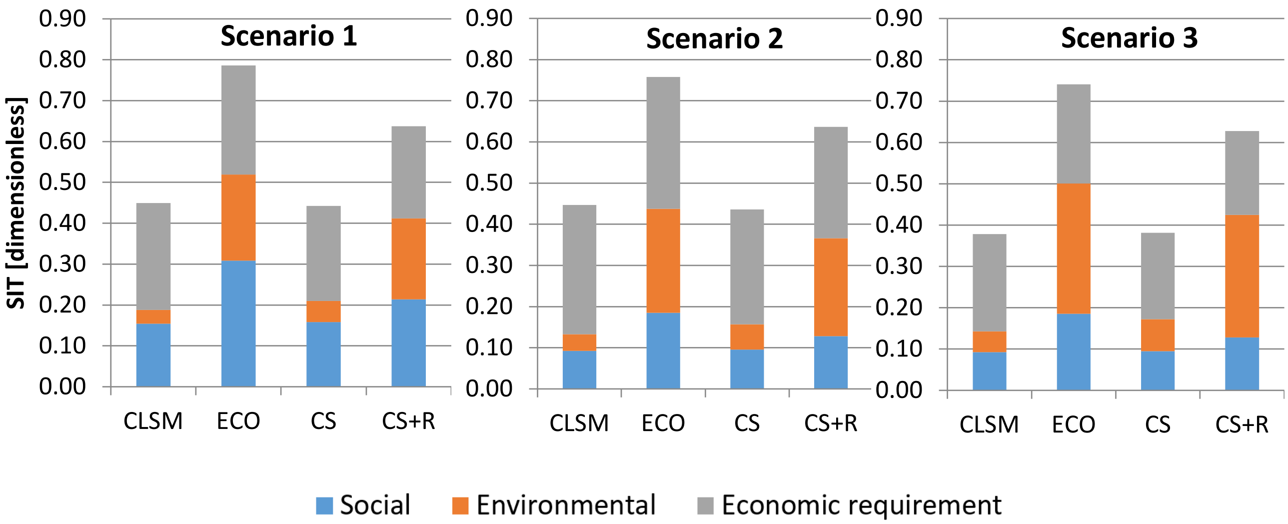

Fig. 5. Resulting SIT for the four alternatives and weight scenarios

5. CONCLUSIONS

This paper presents the Sustainability Index of Trenches (SIT), a new tool for the sustainability assessment of trench construction based on the multi-criteria decision-making model MIVES. A panel of experts contributed to the definition of the weights assigned to the requirements, criteria, indicators and value functions of SIT. The tool has been successfully applied to four types of trenches using different excavation methods and backfills. The sensitivity analysis performed to assess the consistency of the tool yields satisfactory results. The conclusions derived from the study are listed below:

- The economic requirement was found to be pivotal by the panel of experts, followed by the environmental and social requirements; thus showing that the construction costs still represent a major factor in the selection of the trench solution for utility services.

- Among the environmental indicators, the use of reused or recycled materials and the carbon dioxide emissions were selected as the most relevant by the panel of experts, which proves the increasing concern among utility companies and contractors for environmental impacts derived from their business activity.
- The case study presented with four types of trenches has revealed that the eco-trench (ECO) obtains a SIT= 0.80, which is significantly above the other solutions, namely 110.5%, 100.0% and 27.0% for CLSM, CS and CS+R, respectively.
- The detailed analysis of the contribution of each of the requirements to SIT shows that the social requirement yields very similar values regardless of the solution, hence not discriminating among the type of trench. However, significant differences are detected among the solutions for economic and environmental requirements. The economic requirement for the ECO is marked 100%, 91.7% and 43.8% higher than for CLSM, CS and CS+R, respectively. The environmental requirement for the ECO obtained a value that is 450%, 340% and 4.8% higher than for CLSM, CS and CS+R, respectively. The latter values show the relevance of the reuse and recycling of materials in the overall result of SIT.
- The sensitivity analysis showed the robustness of the method as the results show small variations (ranging from 0% to 18.4%) considering the significant changes in the weight assignment in the different scenarios. In all cases, the SIT classification does not change being ECO first, CS+R second and the other two solutions (CS and CLSM) remaining the last.

The Sustainability Index of Trenches contributes to the holistic assessment of new construction processes for trenches beyond the technical feasibility by accounting for economic, environmental and social aspects, thus assisting in the evaluation and prioritisation of trench solutions. The findings and the case study presented can be used as a reference for contractors and utility companies.

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