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Research article

Environmental and economic impacts of combining backfill materials for novel circular narrow trenches

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ABSTRACT

Over the last few years, several policies and new technological solutions have targeted the construction sector with the aim of reducing the sector's impacts on the environment. Among the different technological advances proposed, the reuse of materials in construction has been reported as a promising solution for an increase in sustainability and circularity. In particular, a type of cities' undergrounds assets for which materials' reuse is being explored are trenches for protecting services (i.e., water and gas transport pipelines, and optic fibre and other telecommunications services). Nonetheless, the economic and environmental benefits and impact of this type of system is still insufficiently quantified. In this research study, the economic and environmental impacts of four scenarios of trenches were assessed by using Life Cycle Costing (LCC) and Life Cycle Assessment (LCA). The four alternatives analysed consisted of: (1) the classical solution; (2) the classical solution with the reuse of soil; (3) the control low-strength material, and (4) the eco-trench. The results allowed concluding that in the eco-trench system, for which all material is reused, the environmental and economic impacts could be reduced by more than 80% and 50%, respectively. A parametric study for which the dimensions of the trenches were varied, permitted to reinforce these results and to quantify the impact's change along with the width and depth of the trench. Overall, this study provides a comprehensive view of the high-impact potential of reusing material for the construction of trenches in cities. The outcomes allow also remarking that the eco-trench system could be an attractive and advantageous solution for urban infrastructure stakeholders, both from an economic and environmental perspective.

1. Introduction

The construction industry is one of the most polluting sectors in the world, generating 38% of energy-related greenhouse gas emissions (Giunta, 2020; Nagireddi et al., 2022; United Nations Environment Programme, 2021). While decreasing the construction demand would directly entail a decrease in such environmental impacts, the trends in urbanisation growth indicate that more infrastructure will be needed in the coming years. At present, 55% of the population lives in urban areas (The World Bank, 2020), and by 2045 it is predicted that this figure will increase by 1.5 times. This implies decision-makers need to ensure that all citizens have access to basic services, such as water and sanitation, housing, and transportation. Therefore, sustainable construction solutions need to ensure that demands are met and, at the same time, that their environmental impacts are reduced (The World Bank, 2020). Among all the necessary infrastructure in cities, current centralized gas, water and wastewater services translate into thousands of kilometres of underground pipelines in need of maintenance and upgrades due to aging infrastructure and connections with new residential areas (World Economic Forum, 2014).

In order to limit interference with other services or traffic during construction, some authors have proposed trenchless pipeline systems (Jung and Sinha, 2007; Kaushal et al., 2020). In spite of their social benefits, these systems can be costly, which is why narrow trenches are a

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more common technique to install small-diameter flexible pipelines in cities. Similar to trenchless systems, this technique causes limited interference during construction. However, they generate large amounts of trench arisings. Once the trench is excavated, backfill material is used to fill up the trench and to support the pipe and surface elements. Nevertheless, the extracted material does not necessarily meet the quality and mechanical requirements to be used as pipeline support or embedding material. For this reason, there exist several trench designs that ensure the functionality and protection of the pipeline under varying conditions, which comes at different environmental and economic costs due to the nature of the selected materials (e.g., Petit-Boix et al., 2016a, 2018a). How to select suitable trench designs and backfill materials is still a critical question that needs to be further aligned with current environmental policies and concepts. For instance, integrating a circular economy perspective into urban planning can help take advantage of current urban trends in circular construction and implement overarching principles such as reuse, lifetime extension and eco-design (Ghisellini et al., 2016; Kirchherr et al., 2017; Petit-Boix and Leipold, 2018). To what extent novel designs with circular backfill materials reduce the environmental and economic impacts of cities remains to be seen, which demands a first step toward exploring common designs and their alternatives.

The classical solution (CS) for a trench uses 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 (Blanco et al., 2014). However, several common deficiencies may arise with this method (Casanovas-Rubio et al., 2019; Petit-Boix et al., 2016b). A poor selection of soils or inadequate compaction may lead to settlements and other problems during the service life of the conventional trench, such as critical load concentrations in the pipe and pavement subsidence (Blanco et al., 2014). In this context, the reuse of extracted soil is limited due to the difficulties related to proper selection and separation and the risk of future problems.

Alternatively, instead of compacted soil, the backfill used in narrow trenches can be a cementitious material (i.e., made of a binder, aggregates, water, and admixtures) known as controlled low-strength material (CLSM) (Alizadeh, 2018; Blanco et al., 2014; Etxeberria et al., 2013; Pujadas et al., 2015; Wu et al., 2016). This material is highly fluid to allow the filling of tight and restricted areas in which placing and compaction would otherwise be difficult; however, it is not excessively fluid so that the material may remain in place in trenches with a slope.

However, the above-mentioned solutions, the CS and the CLSM trenches lead to significant raw material consumption and CO_2 emissions associated with material transportation among other environmental, economic, and social impacts. To overcome these drawbacks and promote the reuse of extracted soil, it may be necessary to change the consolidated design and construction philosophy behind the narrow trench system. In this sense, Blanco et al. (2017) presented a more sustainable solution, called eco-trench (ECO), which is based on the re-use of soil.

The idea of reusing trench arisings has already been considered in the UK, where 100 million tonnes of this material are generated per year (Maqbool and Amaechi, 2022) and several pilot experiences have been carried out (Edwards et al., 2007). The so-called ECO trench consists in re-using the trench arising as the main backfill and finishing the trench with a top layer of expansive concrete. This concrete contains a calcium oxide admixture that generates a volumetric expansion during early ages that reduces the likelihood of cracking due to shrinkage. Given its properties, this admixture has been commonly used to compensate shrinkage. Nevertheless, in the case of trenches, not only is the volumetric expansion interesting but also the level of internal stresses generated when the concrete is confined. This may favour the transmission of stresses from traffic loads to the surrounding soil, thus, this relieving the stresses on the backfill material and the pipe. Consequently, the restrictions related to the backfill selection are eliminated, and, consequently, the reuse of the soil being possible without compromising the construction process efficiency and productivity or the performance of the pavement. Moreover, this solution allows avoiding the final layer of asphalt, which entails an additional advantage in terms of execution (no overlaps are required), logistics, and schedule.

To confirm whether these designs result in reduced environmental impacts and economic costs, previous research has applied a life cycle perspective to the system to shed light on hotspots from raw material extraction to the end of life. These studies have especially focused on assessing pipe materials using life cycle assessment (LCA) (Petit-Boix et al., 2016b), but no research has been yet done to assess the backfill material. To assess the degree of sustainability of existing trench designs, Casanovas-Rubio et al. (2019) developed the sustainability index for trenches (SIT) based on the multi-criteria method MIVES (Pujadas et al., 2017, 2019; Roigé et al., 2020) and applied it to a case study. Their analysis highlighted that there exist differences between the types of trenches regarding the economic and environmental aspects. However, the social impacts were very similar for all the alternatives. Thus, the study presented herein focuses on the economic and environmental dimensions. Considering the sheer volume of material and, thus, the impact of the backfilled material in narrow trenches, scarce references can be found in the technical literature regarding the environmental impact associated with resource consumption of these backfill materials alternatives. Therefore, there is a clear need for determining the technically feasible configurations that result in an optimization of resources and, consequently, in minimizing the life cycle environmental impacts and economic costs of the system.

In light of the above, the main goal of this research is to quantify, analyse, and compare the environmental impacts and the economic costs of equivalent backfill material alternatives that integrate circularity principles by using LCA and life cycle costing (LCC); also, the study aims at analysing the eco-efficiency of the alternatives by comparing the environmental burdens and economic cost of backfills. By doing so, specific design conclusions and recommendations are defined, these being meant to be useful for urban planners and urban assets managers.

2. Materials and methods

This study used LCA and LCC for four types of trenches to identify their environmental impacts and their representative costs during their lifetime. LCA is a methodology to assess the environmental impacts of each process involved in the life cycle of a product or service from a systems perspective as defined in the ISO 14040 and 14044 standards (International Organization for Standardization [ISO], 2006a, 2006b).

Similarly, LCC is a method for economic analysis that allows assessing the total costs of a system over its whole life span or over the time during which the service is provided. Thus, an LCC involves an evaluation of costs such as purchase price and associated costs (e.g., transport, installation), operating costs (e.g., energy, water use, maintenance), and end-of-life costs (e.g., disposal). The framework for LCC can be found in ISO 15686–5 (International Organization for Standardization [ISO], 2017), which includes the main principles, processes, calculations, and definitions.

The following sections describe the material and methods utilised in the LCA and LCC. The sections present the standard phases of an LCA, including the definition of goal and scope, the life cycle inventory, the life cycle impact assessment, and the interpretation.

2.1. Goal and scope definition

The goal of this study was to assess and compare the environmental impacts of four types of trenches used to install flexible pipelines of small diameter for the construction of utility services networks. In LCA studies, it is necessary to define a functional unit (FU), which is the reference unit that is used to quantify the performance of the product system. It is common practice to define the FU of systems involving pipes in unit pipeline length (see, for instance, Du et al., 2013; Vahidi et al., 2016). Thus, the FU for this study is 1 linear metre of trench to install a pipe with a diameter of 110 mm. Narrow trenches for the installation of flexible pipelines of small diameter are commonly used for the construction of utility services networks to generate minimum interferences with other urban services. In particular, this technique is frequently used with natural gas pipelines in cities or small villages.

The equivalent designs include (1) a classical solution (CS), (2) a classical solution with reuse (CS + R), (3) a controlled low-strength material (CLSM), and (4) an eco-trench (ECO) (Fig. 1). These solutions were selected based on their relevance and designed to align with previous studies to allow for comparability. In particular, the configuration of the four types of trenches matches that of the trenches analysed in Casanovas-Rubio et al. (2019). An average lifespan of 50 years was assumed in all designs, which were conceived in the state of development of Mediterranean cities, specifically in Catalonia (Spain).

The LCA and LCC consist of equivalent system boundaries (Fig. 2) to enable a systemic integration of the environmental and economic impacts. The processes included are: (1) the trench excavation with a trencher considering five different types of ground, which applies to all solutions; (2) filling of the trench with new or reused material; (3) load and transport of the waste from excavation to an authorised landfill; (4) compaction of the soil, and (5) surface finishing, which is different for each alternative. All the trenches were considered to be located in an asphalt carriageway, which is a common situation in the urban areas where narrow trenches are usually located. The consideration of asphalt is particularly relevant in this study, as its impact has been seen to be relatively important in other studies (Hajibabaei et al., 2020). The maintenance of the trenches was considered to be negligible. The nominal diameter of the pipe was considered to be 110 mm and remains the same for all the sizes of the trenches. However, the price and environmental impact of the pipe were not included in the analysis. Each design has its own particularities when managing backfill materials (Casanovas-Rubio et al., 2019).

- **Classical solution (CS).** The excavated material is carried to a landfill. Afterwards, the trench is filled with a new filling material. On top of the new material, a concrete layer is placed first. Then, 0.05 m of concrete is removed using a milling cutter. An extra width of 0.20 m at each side of the trench is also removed to allow for overlapping with the rest of the pavement. The final step in the production involves placing an asphalt layer of 0.05 m thick as wearing course.
- **Classical solution with reuse (CS + R).** This solution is similar to CS. The only difference is that, instead of using new filling material, the soil that is extracted is then reused on-site.
- **Controlled low-strength material (CLSM).** The filling consists of a fluid mortar of low compressive strength for the whole height of the trench (Blanco et al., 2014; Pujadas et al., 2015). After placing this material, 0.05 m of the top are removed using a milling cutter. An extra width of 0.20 m at each side of the trench is also removed to allow for overlapping with the rest of the pavement. Finally, an asphalt layer of 0.05 m thick as wearing course is placed.

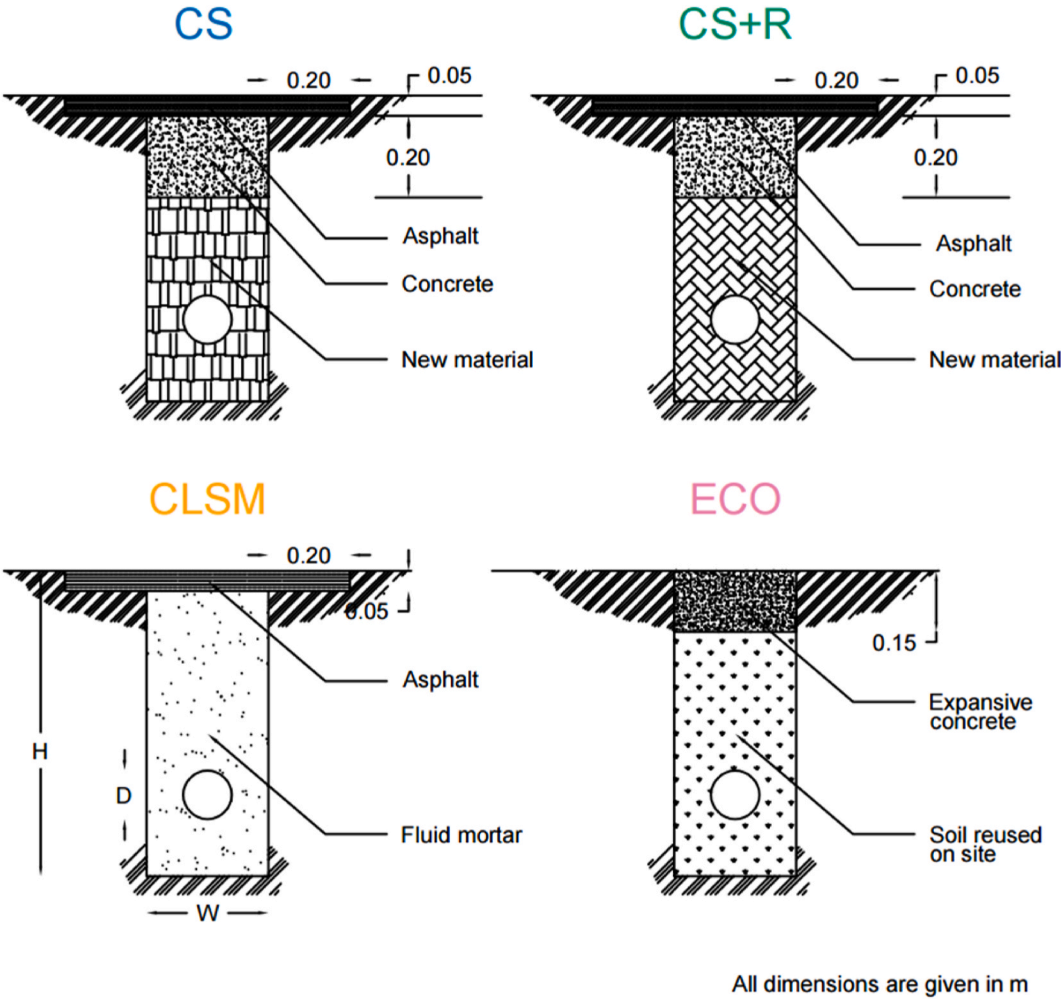

Fig. 1. The four types of trenches considered in the analysis.

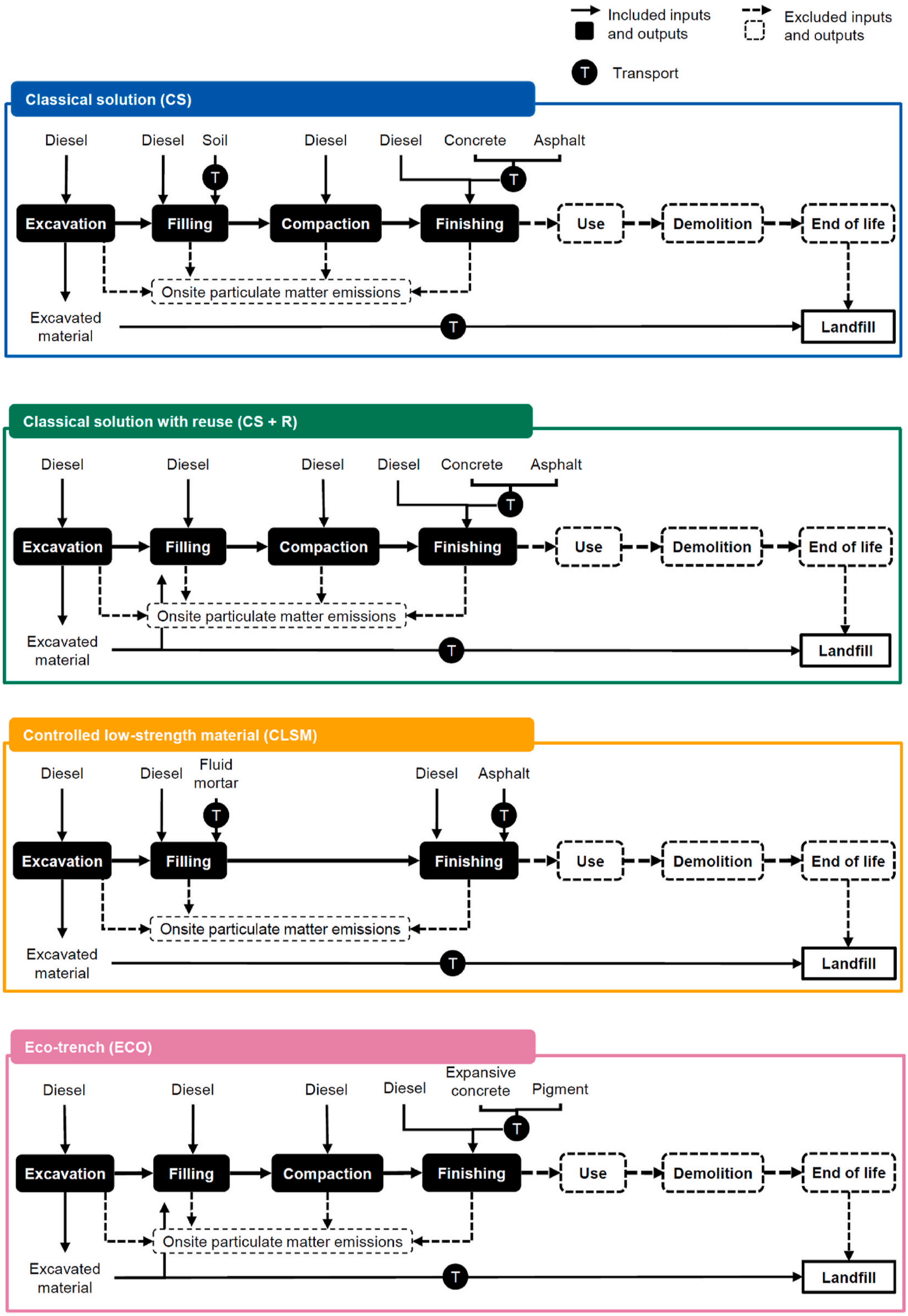

Fig. 2. System boundaries of the scenarios considered.

- **Eco-trench (ECO).** The soil is excavated, and the material extracted is reused up until 0.15 m before the top. The top is then filled with a slightly expansive concrete. This concrete has a black pigment that allows obtaining the same colour as the rest of the asphalt pavement. In this solution, it is not necessary (neither for aesthetic or technical reasons) to add an extra width of 0.20 m at each side for an asphalt layer or overlapping due to the expansive properties of the concrete and pigments used. Further information on the ECO can be found in (Blanco et al., 2017).

In the study by Casanovas-Rubio et al. (2019), a single dimension was considered for the trenches (i.e., 0.15 m width and 0.75 m depth). Nonetheless, in this study, different widths and depths were considered in order to analyse how results change from a parametric perspective. In particular, the studied dimensions are four widths (0.15, 0.20, 0.30, and 0.40 m), and nine depths (0.75, 0.80, 0.90, 1.00, 1.10, 1.20, 1.30, 1.40, and 1.50 m). This results in a total of 36 different trench dimensions, where the smallest one measures 0.15 m × 0.75 m, and the biggest one measures 0.40 m × 1.50 m.

2.2. Life cycle inventory (LCI)

The LCI process involves developing an inventory containing the data corresponding to the input and output flows for the product system. In this study, data for the inventory was collected from local construction companies, construction databases and the life cycle database ecoinvent 3.3 (Ecoinvent, 2017) for background data. The public database BEDEC, developed by the Catalan Institute of Construction Technology (ITeC), was used to obtain detailed information on the processes and materials for each of the four trenches (ITeC, 2019). This database provides technical and monetary information for a high number of elements used in the construction sector. The reference year for the LCI was 2019.

Based on the dimensions modelled in each trench design, we created the LCI using the unitary processes included in the BEDEC database, which include material amounts and composition, energy consumption of construction equipment and unitary prices for labour and infrastructure.

As for the transportation distances, we assumed 30 km for the transport of backfill materials to the construction site and 10 km for the transport of waste soil to the landfill (Petit-Boix et al., 2014, 2016a).

The economic costs included were the direct costs (e.g., labour, materials, plant, and auxiliary costs), whereas the indirect costs, overheads and industrial profit were excluded. In particular, the costs included were the ones corresponding to trench excavation; loading, transportation, and controlled disposal of the waste to landfill; necessary backfill material; compacting; and surface finishing. The necessary labour and energy were included in the prices used. A breakdown of these costs can be found in the Supplementary material.

Excavation and backfill processes demand additional specifications. The price used for the excavation with the trencher was provided by Calaf Trenching S.L. for a trench of 0.35 m × 1.10 m. The excavation costs for other dimensions were calculated proportionally according to the trench dimensions. Additionally, these costs were calculated considering five different types of soils that are described in the Spanish standard (Ministerio de fomento, 2019), namely soft soil, compact soil, soft rock, medium rock, and hard rock. The considered bulking factors for the excavation were defined as follows: 1.20 for soft soil, 1.30 for compact soil and soft rock, and 1.40 for medium and hard rock. Regarding the compacted soils, three different types of soil had to be considered. The Spanish Government defines the following three types of soil: selected, suitable, and tolerable (Gobierno de Espana, 2017). Note that this definition and the specifications of each group may vary in other countries. This definition is relevant to this study because the cost corresponding to compacting changes depending on the type of soil.

Given the five and three classifications for excavation and compaction respectively, the cost per linear metre of each type of trench was calculated for each one of the 15 combinations of excavated ground and backfill material. In particular, the costs for each dimension were calculated, and then an (unweighted) arithmetic mean of the cost of the 15 combinations of excavated ground and backfill material was calculated for each type of trench. Using an unweighted mean carries the consequence that the cost utilised for the study does not consider the frequency of appearance of each combination of excavated ground and backfill material. In the end, the process above yielded a total of 45 tables, one for each size of the trench. Note that the CLSM trench has mortar as filling and, thus, the classification of backfill material did not apply.

Regarding the prices related to the landfill, it was considered that, for the CLSM and CS, the waste corresponds to the whole volume excavated including the bulking. For the ECO and CS + R, the volume that is transported to landfill is lower, given that part of it is reused in the trench. The specific proportion that is taken to landfill for different dimensions of the trench can be found in the Supplementary material.

In the ECO trench, the lime used was Link EVR, white F2000 and F2000-Ad from Cales de Pachs S.A. The used pigment was a micronized black iron oxide produced by a special process that provides a higher dispersability and brightness (NB-5970 model from Nubiola). The pigment is dusted on the surface with an amount of 50 g of pigment/m^2 of surface.

2.3. Impact and cost assessment

The life cycle impact assessment stage is the step where the impacts are evaluated based on the LCI data. This impact assessment was carried out to calculate the environmental impacts of each design. Such assessment was performed using the ReCiPe (H) method (Huijbregts et al., 2016) and the OpenLCA 1.9.0 software.

The LCA includes the mandatory classification and characterisation steps. The following impact categories were selected: Global warming, Stratospheric ozone depletion, Terrestrial acidification, Marine eutrophication, Freshwater eutrophication, Photochemical ozone formation, Mineral resource scarcity, Fossil resource scarcity, and Water use. These impact categories represent the core environmental impact indicators of the standard EN 15804 + A2 (European Standards [EN], 2019), and they were selected based on their relevance to the cases studied and to allow for comparability with other similar studies. None of them was discarded to avoid burden shifting.

The cost analysis focuses on the total cost of the infrastructure. As the operation and maintenance are excluded from the analysis, the costs are reported for the entire lifespan of the system (i.e., 50 years). Given this exclusive focus on direct costs of construction, the authors chose not to estimate the time-bound present value and annual equivalent costs.

2.4. Interpretation

In the last step of the LCA, the information from the results of the LCI and the life cycle impact assessment are evaluated, and conclusions are extracted. In this study, the interpretation of the results was performed primarily using the results for the two extreme dimensions. Namely, the smallest (0.15 m × 0.75 m) and the largest (0.4 m × 1.5 m) sections were used to obtain an initial understanding of the results.

Some authors have highlighted that analyses in the context of underground infrastructure are prone to be affected by high uncertainties. Thus, in this study the data collection focused on several different dimensions and soil types instead of a single one, which was useful to understand how results change with different assumptions (Hajibabaei et al., 2020). In particular, sensitivity analyses were performed on the alternative scenarios by changing the dimensions as described above. Results from the sensitivity analyses were used to understand to what extent the main system parameters and assumptions may influence the outcomes from the LCA and the conclusions drawn.

2.5. Eco-efficiency assessment

The eco-efficiency of the alternatives was assessed by combining the evaluation of the environmental and economic impacts. The assessment was performed following ISO 14045 (International Organization for Standardization [ISO], 2012), which describes the principles and requirements for this type of analysis.

In this study, the same approach as in (Petit-Boix et al., 2018b) was taken. Namely, the results of LCC were used to assess the monetary value of the alternatives, and they were compared to the environmental dimension by using a graph.

3. Results and discussion

In this section, the environmental and economic performance of the trenches is presented in Sections 3.1 and 3.2, respectively. In each of the sections, a sensitivity analysis to assess the difference in results when varying the dimensions of the trenches is presented. An analysis of the eco-efficiency is provided in Section 3.3.

3.1. Environmental life cycle assessment

3.1.1. Results of the LCA

The potential environmental impacts associated with the classical solution (CS), classical solution with reuse (CS + R), controlled low-strength material (CLSM), and the eco-trench (ECO) are shown in Fig. 3.

Comparing the alternative trenches, the results indicate that the eco-trench (ECO) has much lower environmental impacts (between 80% and 97% less) than the other three solutions in all impact categories. This is directly related to two aspects. First, fewer new materials are needed for this alternative, given that almost all the filling is reused except for the expansive concrete. This alternative avoids using asphalt, which contributes to the highest impacts in almost all impact categories and all alternatives (Giunta et al., 2020; Praticò et al., 2020). Second, a lower use of new materials is linked to less energy and equipment needed for the stages of filling, compacting, and finishing.

For the ECO trench, the backfill material is the main contributor to the total impact for impact categories Global warming, Marine eutrophication, Freshwater eutrophication, Mineral resource scarcity, and Water consumption. In these impact categories, the process involving the backfill material represents between 54 and 90% of the total impact (with a mean of 79% and 73%, and a standard deviation of 8% and 10% for the trenches with dimensions 0.15 m × 0.75 m and 0.4 m × 1.5 m, respectively).

Energy is the main contributor to the overall impacts for impact categories Stratospheric ozone depletion, Acidification, Ozone formation, and Fossil resource scarcity. Nonetheless, in this case, the contribution of each of the stages is not as extremely distributed as in the case described above. In these impact categories, the diesel makes up between 36.7 and 71.3% of the total impact (with a mean of 46% and 57%, and a standard deviation of 9.2% and 8.9% for the trenches with dimensions 0.15 m × 0.75 m and 0.4 m × 1.5 m, respectively).

System CLSM has the highest impacts in 7 out of 9 impact categories (i.e., Global warming, Stratospheric ozone depletion, Terrestrial acidification, Freshwater eutrophication, Photochemical ozone formation, Fossil resource scarcity, and Water use) in the case of the small trench, whereas the impacts are the highest in 8 out of 9 impact categories for the bigger trench (i.e., for Marine eutrophication as well).

In this trench system, the finishing process (which involves the use of asphalt) is responsible for the highest proportion of the impacts. More specifically, for the case of the 0.15 m × 0.75 m trench, between 78.47% and 95.89% (average of 88.03% and standard deviation of 5.28%) of the total impact is given by this process, whereas for the 0.4 m × 1.5 m, it is between 48.85% and 86.71% (average of 69.71% and standard deviation of 10.89%) of the total impact. This is supported by the findings in Giunta et al. (2020) and Praticò et al. (2020).

The trench system CS has the highest impacts in two impact categories, namely Mineral resource scarcity and Marine eutrophication. Regarding Mineral resource scarcity, while the amount of asphalt (and therefore its corresponding environmental impact) for CS, CS + R and CLSM is similar, the impact of the backfill material for CS is higher. This is because CS uses concrete, which is linked to high impacts in terms of minerals depletion.

Regarding Marine eutrophication, the impacts are highest for CS when considering dimensions 0.15 m × 0.75 m, and for CLSM when considering dimensions 0.4 m × 1.5 m. Nonetheless, the difference between CS, CS + R and CLSM in this impact category are very low (less than 5% and 10% for the smaller and bigger sections, respectively).

The results in this work are in accordance with previous research on environmental impacts of pipe and road infrastructure. Moretti et al. (2018) found that using low-impact procedures and using secondary raw materials provide better overall environmental results in all impact categories considered. Fathollahi and Coupe (2021) also found that lower necessary material requirements for the construction resulted in lower impacts in several stages of the life cycle. Petit-Boix et al. (2015) evaluated the environmental impacts of a sewer construction and found that using concrete as bedding material can have a significant environmental impact during construction. Therefore, the selection of materials has an important effect on the final environmental consequences.

Several studies have discussed in the past the proportional impact that the transportation phase has on the final environmental impacts. In this study, transportation had a low contribution to overall environmental impacts (accounting for less than 4% in all impact categories, except for fossil resource scarcity, where the impacts were around 7% of the total impact). This aligns well with the results of Morera et al. (2016), which showed that the impact from transport accounted only for less than 4% of the total impacts; and of those in Hajibabaei et al. (2018), who found that the transportation stage represents, in average, less than 20% of the impacts.

3.1.2. Sensitivity analysis

The results shown in the previous section corresponded to the two extreme cases of trench sections analysed. Fig. 4 shows the potential environmental impacts for the impact category Global warming. Note that similar graphs for the remaining impact categories can be found in the Supplementary material.

As the results of the smallest and largest trenches showed, the ECO still shows the lowest environmental impacts for all the dimensions analysed, even for the largest sections. Regarding the highest environmental impacts, these are achieved by the larger sections of the CLSM. Below sections of 0.3 m^2, some of the CS and CS + R alternatives have higher impacts than the CLSM.

In addition to the above, it can be observed that results for ECO are less spread than those of CLSM ($\sigma_{ECO} = 6.02, \sigma_{CLSM} = 36.41$).

Besides, the results of CS and CS + R show similar spreadness ($\sigma_{CS} = 23.81, \sigma_{CS+R} = 21.70$). This indicates that the impact of reusing part of the excavated material does not bring significant benefits in Global warming terms.

3.2. Life cycle costs

3.2.1. Results of the LCC

The LCC results for the smallest and largest trench alternatives (0.15 m × 0.75 m and 0.4 m × 0.15 m, respectively) are presented in Fig. 5. They have been broken up into representative life cycle stages, including excavation, filling, compacting, finishing and end of life.

In the case of the smaller trenches (0.15 m × 0.75 m), the process of finishing represents the largest cost in the CS, CS + R and CLSM solutions (corresponding to a 52%, 63%, and 37% of the total cost respectively). This is not the case of the ECO, where the costs of the different stages are evenly distributed, from 19.14% to 32.54% of the total cost. This is mostly because the finishing of the former three solutions requires extending a 20 cm layer to ensure adherence to the pavement.

In the case of CS, CS + R, and ECO, proportionally, the lowest costs correspond to the filling (less than 2.2%). Particularly, for CS + R and ECO, this is because the necessary filling material is reused and thus no costs are attributed to the filling stages.

Differently from the above three solutions, the filling for CLSM corresponds to 25% of the total costs, given that the material used to fill the trench has certain strength requirements that increase its corresponding price. The lowest cost in the case of CLSM corresponds to the compacting process due to the fact that no compacting process is necessary.

Looking at the overall costs, the alternative with the highest costs is the CLSM. Nonetheless, the second most expensive alternative is CS,

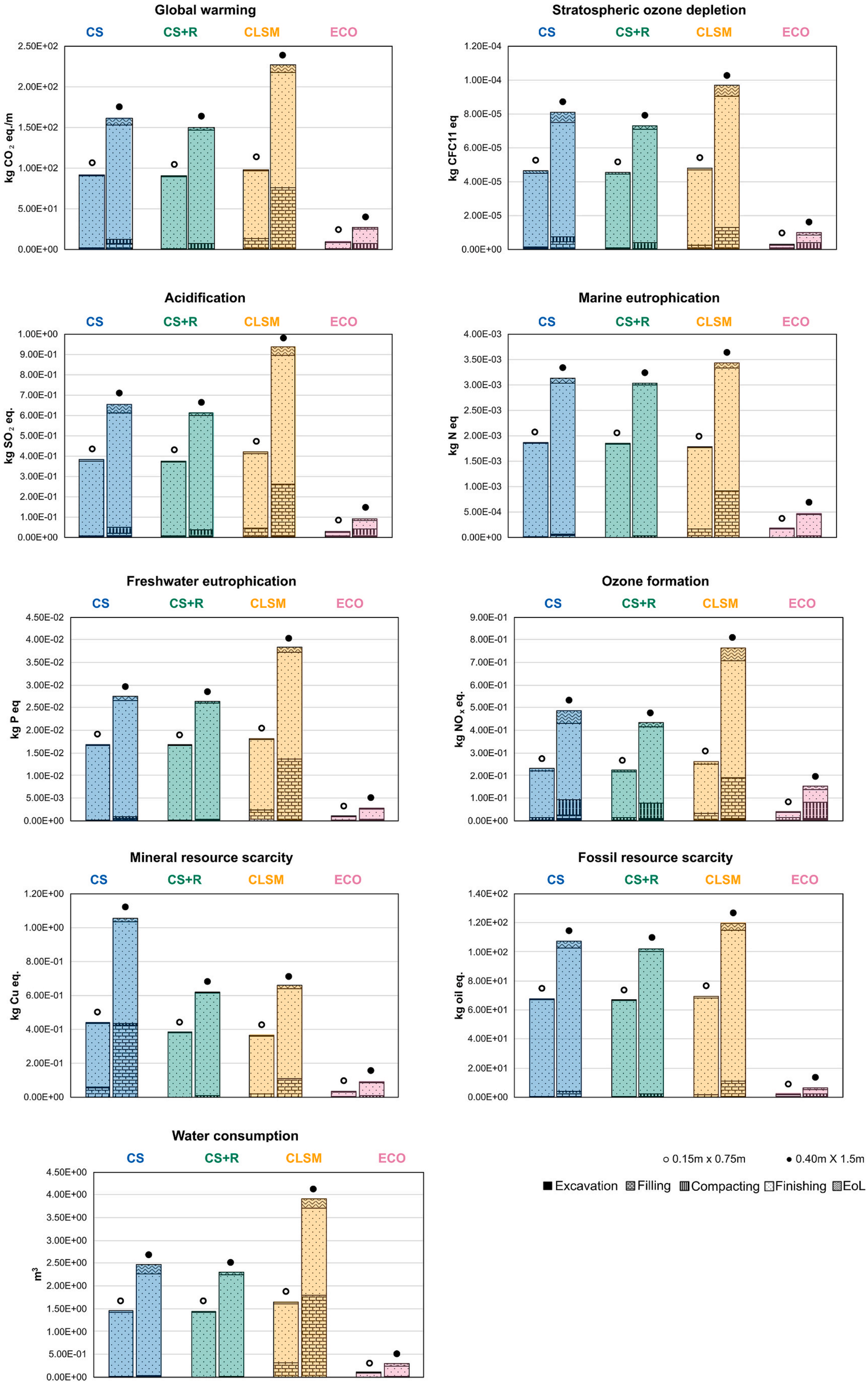

Fig. 3. Potential environmental impacts for the four alternatives (CS: classical solution; CS + R: classical solution with reuse; CLSM: controlled low-strength material; ECO: eco-trench).

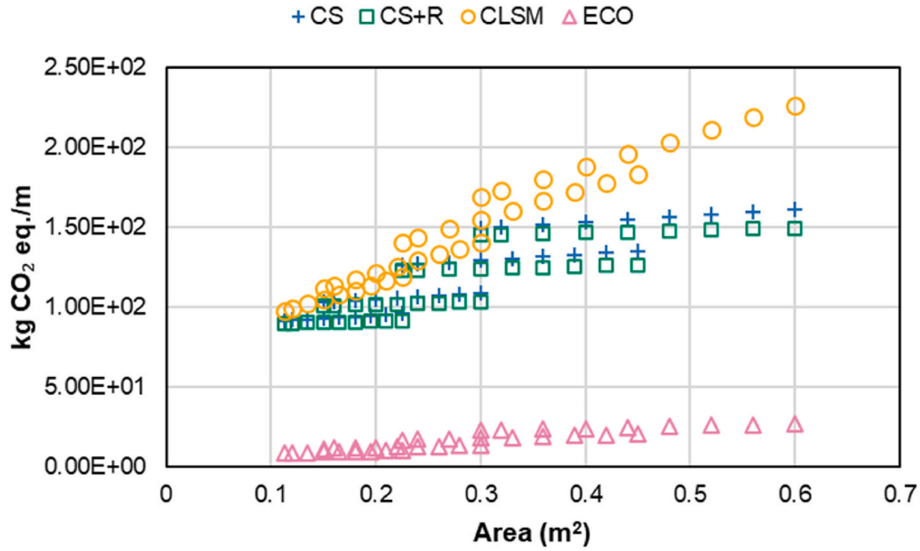

Fig. 4. Potential environmental impacts (for impact category Global warming) of different areas of the trench for each of the 4 alternatives (CS: classical solution; CS + R: classical solution with reuse; CLSM: controlled low-strength material; ECO: eco-trench).

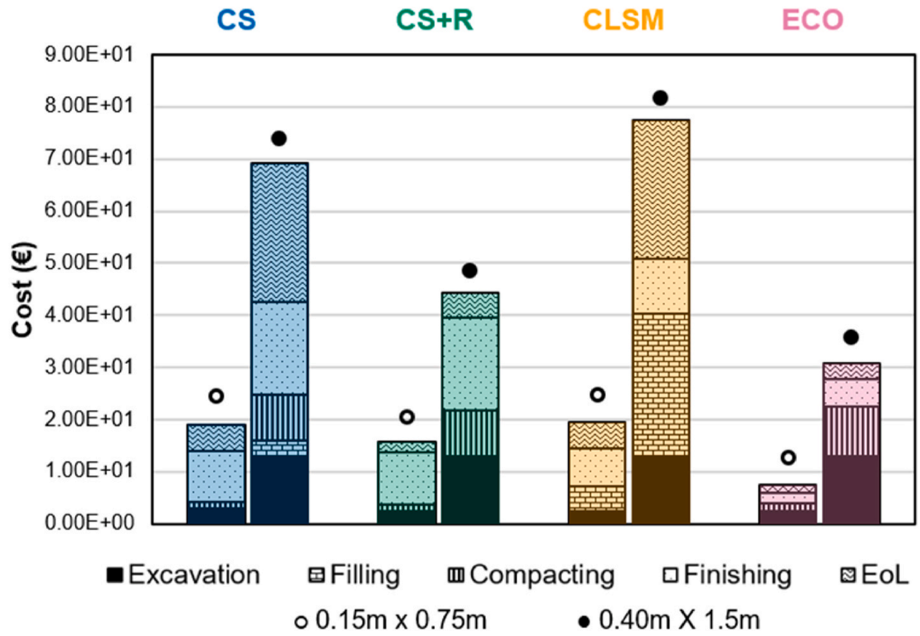

Fig. 5. Costs per linear metre of a 0.15 × 0.75 m and a 0.4 × 1.5 m trench for each of the 4 alternatives (CS: classical solution; CS + R: classical solution with reuse; CLSM: controlled low-strength material; ECO: eco-trench).

with a difference of less than 2% with respect to CLSM.

In the case of the larger trenches (0.15 m × 0.75 m), the costs represent, on average, an increase of 40% with respect to the smaller trenches (0.4 m × 1.5 m). For these dimensions, the process of finishing represents the highest proportion of the cost only for the CS + R (contributing by 40.07% of the total cost). The most expensive process is the end of life for CS (38.61% of the total cost) due to the higher volume of material that is loaded in trucks and transported to landfill, the filling for the CLSM (35.34% of the total cost), and the excavation for the ECO (41.86% of the total cost).

Concerning the overall costs, the most expensive alternative is still CLSM. However, in this case, the difference with respect to the next most expensive alternative, CS, is higher (12%).

3.2.2. *Sensitivity analysis*

As it was done in the LCA, a discussion is included here on how the costs change together with changes in the areas of the trenches. Fig. 6 shows the costs per linear metre of different areas of the trench for each of the four alternatives. As can be seen, there exists a linear relationship between the area of the section of the trench and the life cycle cost.

As the results for the smallest and biggest sections showed, the alternative with the lowest costs is always ECO if the section remains the same, followed by CS + R. Again, this is because of the great number of materials that are reused. The area remaining the same, ECO has lower costs than CS + R because it does not require the milling and asphalt layer operations.

The highest costs correspond to the CLSM trench, followed by the CS solution. These two alternatives do not reuse soil on site. Therefore, the costs increase owing to the borrowing and transportation of materials,

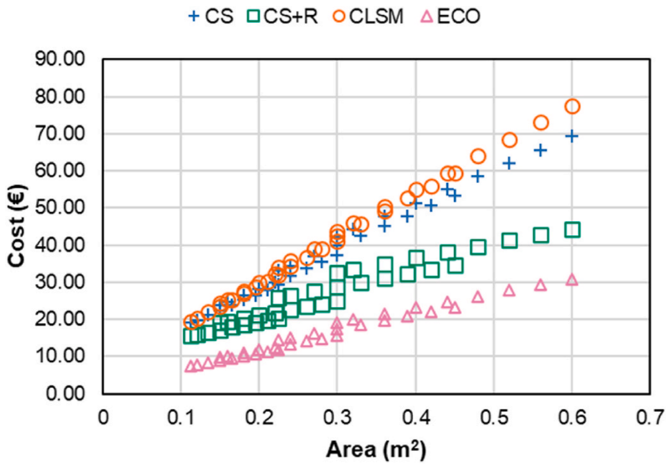

Fig. 6. Costs per linear metre of different areas of the trench for each of the 4 alternatives (CS: classical solution; CS + R: classical solution with reuse; CLSM: controlled low-strength material; ECO: eco-trench).

transportation of waste, and landfill costs.

3.3. *Eco-efficiency*

Fig. 7 shows the results corresponding to the impact category of Global warming and the costs per linear meter of the different trenches analysed. The graph can be interpreted as the eco-efficiency for the different alternatives, where the bottom left part of the graph represents the most efficient solutions (low environmental impact and low costs), and the top right part of the graph depicts the least efficient solutions (higher environmental impact and costs). The impact category of Global warming has been chosen here given its particular relevance. Eco-efficiency graphs corresponding to the remaining impact categories can be found in the Supplementary material.

As observed, the most efficient solutions correspond to the ECO trenches. For the smaller sections, the results show that they have the lowest costs and environmental impacts. However, for bigger dimensions, their costs are comparable to those of the smallest dimensions of CS + R, CS, and CLSM.

The least efficient trenches correspond to the CLSM trenches. The previous sections showed that they have the higher impacts both in the LCC and the LCA of this solution and, therefore, it is evident that they are also the least efficient alternatives. Nonetheless, it needs to be observed that only the 0.40 m × 1.40 m and 0.40 m × 1.50 m are the least efficient ones. For smaller dimensions, while the CLSM still has higher environmental impacts, the range of the cost is the same as the CS.

There is a range of sections where the CS, CS + R and CLSM could yield similar environmental impacts and costs if the section is not the same. It corresponds to the range between 15 and 45 €/m.

Having said this, it needs to be mentioned that the results shown are for the same assumptions regarding transportation distances. Transportation distances not only could influence the total environmental impacts, but also the costs. Additionally, the relationship between changes in environmental impacts and costs in comparison to transportation distances is not necessarily linear. Thus, this is acknowledged as a limitation of this study.

While this study focused on economic and environmental impacts, an important aspect that might be hindering the deployment of more environmentally and economically friendly alternatives are social issues. Some examples of such issues could be culture and tradition-related aspects, the training of workers, or regulations that do not allow for more innovative solutions.

While previous studies have analysed some social impacts arising from these elements, the indicators used were limited. For instance, Casanovas-Rubio et al. (2019) analysed the social impact of the same typologies of trenches studied here using two indicators: inconveniences to the surroundings and occupational risks. They concluded that these social indicators did not have a significant influence on the overall sustainability of the trenches. Nonetheless, a more in-depth social impact assessment could provide more information. Therefore, it is suggested that further studies focus on carrying out thorough social analyses using, for instance, Social LCA (S-LCA).

4. Conclusions and recommendations

The study presented in this paper consists in a comprehensive life cycle assessment and life cycle costing of the most representative and relevant current trench systems. The aim of the paper was to compare the environmental impacts of four systems of trenches for pipe installation (i.e., the classical solution, the classical solution with part of the materials reused, a solution with controlled low-strength material, and the eco-trench, in which most of the material is reused).

In economic terms, results indicated that the eco-trench (ECO) yields between 30 and 63% lower costs with respect to the other three alternatives for all the dimensions. In general, the finishing process leads to the highest costs. Regarding environmental impacts, results indicated

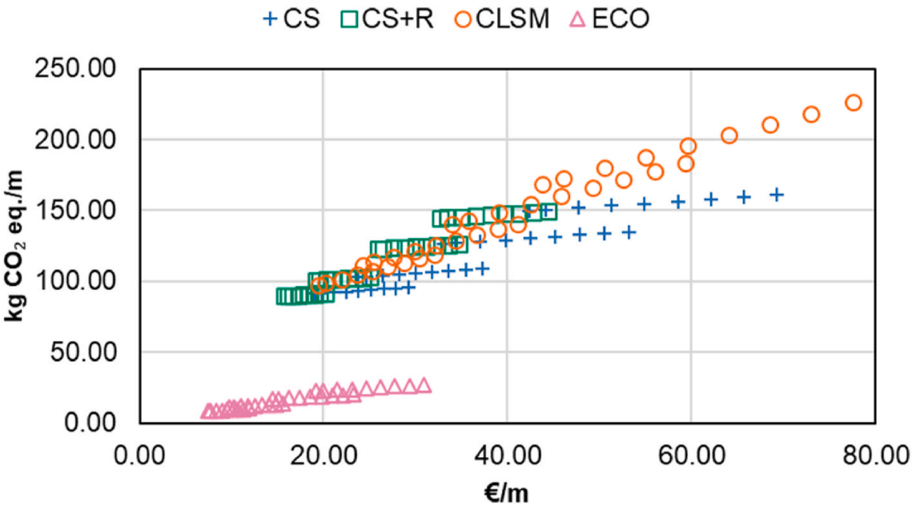

Fig. 7. Global warming and costs per linear metre of different areas of the trench for each of the 4 alternatives (CS: classical solution; CS + R: classical solution with reuse; CLSM: controlled low-strength material; ECO: eco-trench).

that the eco-trench (ECO) had lower impacts (from 80,1% to 97,4% less) in all the impact categories considered. This was mainly due to (i) reusing materials and not using asphalt; (ii) few processes involved. The highest impacts were attained by the solution with controlled low-strength material (CLSM), which was found to have the worst impacts in 7 out of 9 impact categories. These higher impacts were strongly related to high quantities of asphalt necessary.

To address the limitations of this article, future studies could focus on improving the methodology used by modelling the uncertainties of some stochastic variables (assumed as deterministic for this research), and conducting a consequential LCA instead of an attributional one. Furthermore, in this study, the average of the different types of excavated and compacted materials was used in the LCI. Instead, future studies could assess the environmental and economic dimensions of each type of material.

Additionally, there are several research avenues that could be addressed in the future that were beyond the scope of this study. First, it would be interesting to use S-LCA to analyse potential social opportunities and challenges, as it is an important aspect when considering health and safety implications and disruptions to the local community. Second, the impacts from the systems studied in this article could be evaluated in comparison to trenchless systems.

Solutions such as the eco-trench, where most material is reused on-site and no asphalt is needed, represent a promising alternative for achieving sustainability goals within the construction sector. This case illustrates how circular strategies applied to urban infrastructure have great potential to transform our cities and reduce their environmental impacts. For instance, the ECO trench might change the urban landscape due to its lack of asphalt layer and may thus influence the transportation sector, among others. Reusing materials and eco-designing underground infrastructure shows that urban systems are interconnected and that urban planning needs to go hand in hand with technical innovations in the built environment. By doing so, we will not only improve the eco-efficiency of the pipeline system but also rethink the overall material and energy use in closely related sectors involved in the metabolism of our cities. With our example, we thus encourage the academic community to expand this knowledge on the effects of circular strategies on the sustainability of the built environment, which needs urgent answers to pursue a viable transformation towards global sustainability goals.

Credit author statement

Josa, I.: Formal analysis, Data curation, Writing – original draft, Visualization, Petit-Boix, A.: Conceptualization, Methodology, Formal analysis, Writing – original draft, Casanovas-Rubio, M. M.: Conceptualization, Methodology, Formal analysis, Writing – original draft, Pujadas, P.: Conceptualization, Methodology, Writing – review & editing, de la Fuente, A.: Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118020.

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