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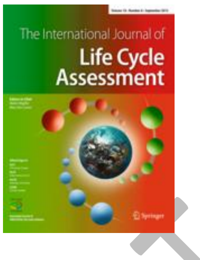

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Life cycle assessment of construction and renovation of sewer systems using a detailed inventory tool

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ABSTRACT

Purpose: The objective was to provide comprehensive life cycle inventories for the construction and renovation of sewers. A detailed inventory was provided with multiple options of pipe materials, diameters and site-specific characteristics, and was embedded into an Excel®-based tool. The tool allows for life cycle evaluation of different sewers. It was applied to determine the most important phases, processes and related parameters involved in the construction and renovation of sewers from an environmental and economical perspective.

Methods: Comprehensive life cycle inventories (LCIs) for sewers construction and renovation were obtained by first identifying all processes involved after interviewing construction experts and reviewing sewer construction budgets from a Catalan company; and second transforming the processes into masses of materials and energy usage using construction databases. In order to run the life cycle inventory analysis (LCIA) the materials and energy typologies from the inventories were matched to their corresponding equivalents into available LCI databases. Afterwards the potential impacts were calculated through the use of LCIA characterization factors from ReCiPe. Life cycle assessment (LCA) was run several times to assess the construction of 1-km long sewer with varying pipe materials, life spans for each material, diameters, transport distances, site-specific characteristics and pipe deposition options.

Results and discussion: The environmental impacts generated by construction and renovation of a 1 km Polyvinylchloride (PVC) pipe with a diameter of 40 cm are mainly associated with pipe laying and backfilling of the trench. The evaluation of several pipe materials and diameters show that the exclusion of regular renovation would underestimate the impacts by 38 to 82% for different pipe materials and diameters. Including end-of-life phase for pipe materials such as PVC increases climate change and human toxicity significantly. The preferred pipe materials from an environmental point of view are precast concrete and High-Density Polyethylene (HDPE). Soil characteristics of the underground and material life span have a high impact on the overall environmental profile, whereas changes in transport distances have only a minor impact (<4%).

Conclusions: Environmental impacts during the construction of sewers are affected by material type, local conditions (e.g. soil conditions) and material lifetime. Consequently, regular renovation has a large influence on all potential environmental impacts and costs and, hence, should not be omitted in LCA studies. In addition to the choice of pipe material (HDPE being the preferred material in this study), backfilling and end-of-life of pipes are the most relevant processes in the environmental burden of sewers.

Keywords: Life span, sewer pipe, life cycle assessment, construction, renovation

1. INTRODUCTION

Human activities in households and industries consume large amounts of water which have to be treated before being returned to the freshwater ecosystems. Above 80% of population in 14 of the EU Member states are connected to urban wastewater treatment plants (WWTPs) (European Environment Agency, 2013), which have the function of removing contaminants from the used water (i.e. wastewater). Sewer systems are the elements that collect and transport wastewater from households and industries to the WWTPs. Despite the important role they have, their construction generates environmental impacts associated to the direct emissions generated on-site and to the production of energy and resources required. Life cycle assessment (LCA) is a widespread tool to assess the environmental impacts from urban water systems (UWS) (Loubet et al., 2014), including drinking water treatment, distribution systems, sewer systems and WWTPs. Many of the studies published so far include the operation but neglect (or partially consider) the environmental load of the construction and end-of-life phases. The review from Loubet et al. (2014) concluded that only three out of eighteen studies included the pipe materials (either in sewers or in drinking-water distribution networks) in the inventory phase and none considered the civil works involved in the construction of sewer systems. Risch et al. (2015) is the first study that compared in detail the environmental impacts from the construction and operation of a case-study which included a sewer system and a WWTP. Risch et al. (2015) provided a detailed inventory including pipe materials and civil works for the construction of one specific sewer system.

Focusing on pipe networks (either for sewers or for drinking-water distribution), three studies have addressed in detail their construction following a life cycle approach. Piratla et al. (2012) compared four pipe materials (molecular oriented polyvinylchloride (PVC-O), polyvinylchloride (PVC), high-density polyethylene (HDPE) and ductile iron) in terms of CO_2 emissions from their manufacturing and assumed a lifespan of 50 years for all materials evaluated. Du et al. (2013) compared six pipe materials (PVC, ductile iron, concrete, HDPE, reinforced concrete and cast iron) in terms of global warming potential (GWP) and considered pipe production, transport, installation and use phases and assumed a service life of 30 years for all pipe materials. Petit-Boix et al. (2014) followed a multi-criteria LCA approach (involving several potential impact categories) to evaluate pipes made from PVC, concrete and HDPE and assumed that plastic pipes had to be replaced once every 100 years. The three studies differ in the phases and processes considered in the construction of the pipe networks, did not model in detail renovation of the infrastructure and made different assumptions regarding their life span.

Construction and renovation (particularly for sewers) are not systematically included in LCA studies of UWS due to the limited availability of comprehensive life cycle inventories which account for different diameters, a variety of characteristics of the site, multiple materials with varying life span and several options for pipe disposal. Hence, the objective of this study is to provide comprehensive life cycle inventories for the construction and renovation of sewer systems. This inventory was embedded into an Excel®-based tool, which allows for effective life cycle evaluation of different sewer typologies. By using the tool it was possible to determine which are the most important phases, processes and related parameters involved in the construction and renovation of sewers from an environmental and economical point of view.

2. METHODOLOGY

2.1. Description of sewer pipes construction and renovation phases and processes

The sewer system construction process can be divided into six different phases (Figure 1a): (1) the working area is cleaned; (2) the trench is excavated and underpinned; (3) the pipe is layed at the bottom of the trench above a layer of draining material; (4) the trench is backfilled with granite sand until 30 cm above the pipe and normal sand, which is taken from the same workplace, or sand taken from elsewhere; (5) if there is a road on top of the trench, a layer of asphalt is included, and (6) the unused excavated soil is distributed around the working area or transported and deposited in a landfill.

[place Figure 1 in here]

Three type of trenches can be considered for the construction of sewers depending on the site characteristics. Rectangular trenches are applied for rocky soils and for most compact soils (Figure 2a and b). When the excavated soil is soft a trapezoidal trench is applied (Figure 2c). If asphalt is placed in the upper part of the trench deeper trenches are needed (Figure 2a). The trench type shown in Figure 2b is the selected for the analysis conducted in this paper, even though the Excel® spreadsheet tool created considers the three options.

[place Figure 2 in here]

To renovate a sewer, six different phases are considered (Figure 1b): (1) breaking the asphalt layer and deposition of the material; (2) excavation of the trench; (3) extraction of the old pipe; (4) substitution with the new pipe; (5) backfilling the trench and (6) including a layer of asphalt when is necessary. Finally, during the renovation, it is also necessary to include the end-of-life processes, i.e. to extract and deposit/incinerate the pipe, which also includes its transport.

Each phase comprises different processes such as materials production and transport, consumed diesel from machinery work and disposal (incineration or landfilling). Work area cleaning phase includes the energy consumption process. Excavation phase includes diesel consumption by the machines and transportation of the excess material to a landfill. Pipe laying phase includes the production of the pipe, its transport to the workplace, the diesel consumed during the pipe laying and water consumed to proof its reliability. Backfilling phase considers the granite sand extraction/production, its transport to the workplace and diesel and water consumed during its placement. Asphalt placement phase includes the asphalt production, its transport to the workplace and its placement. The soil distribution around the work accounts for the diesel consumed.

2.2. Life Cycle Assessment

The environmental assessment was conducted following the ISO 14040 and 14044 standards (ISO 14040, 2006; ISO 14044, 2006) which define four stages: (1) goal and scope definition; (2) inventory analysis; (3) environmental impact assessment; and (4) interpretation. Even though process-based LCA is a very time and data-intensive process (Murray et al., 2008), this approach was followed by including specific process of construction and renovation of sewers. Being aware the hybrid LCA would reduce uncertainty from the selection of the boundaries by covering the entire supply chain (Noori et al., 2015), for this particular study the analytical benefits of hybridization did not outweight its costs and hence was not applied (Udo de Haes et al., 2004).

2.2.1. Goal and scope definition

The goal of this life cycle assessment was to compare the environmental impacts from the construction and renovation of several sewer system typologies and to determine which are the phases, processes and related parameters contributing the most to the environmental impacts. As a starting point a hypothetical sewer system with a length of 1 km and a PVC pipe with a diameter of 40 cm was evaluated (this is the initial system from now on). It was considered that the sewer is located in a non-urban area without traffic (no asphalt placement in the upper part of the trench). The pipe was installed in a compact soil zone within a rectangular trench with no shoring (Figure 2b). Distances of 50, 30 and 25 km were selected for the transport of granite sand and sand, asphalt and pipe distributors (Personal communication with Voltes S.L.U. company), respectively, which also coincides with the assumptions taken in Petit-Boix et al. (2014). It was assumed that the surface to be cleaned was the double of the trench surface in the upper part. Because an average life span of 25 years for PVC pipes, in the evaluation, the construction of the sewer plus two renovations were considered. The functional unit of the entire study was the construction and regular renovation of a sewer system of 1 km length during 70 years of operation. The system boundaries are shown in Figure 3 and include direct emissions generated on-site (e.g. air emissions to the ecosphere from diesel combustion) and indirect emissions related to diesel and material production, pipe material deposition and transport. Even though the Excel®-based tool provides estimations of water consumption during the construction process, it has no effects in this study since the water is considered that is directly extracted from the nature.

[place Figure 3 in here]

After evaluation of the environmental impacts of the initial sewer system defined above, a sensitivity analysis was conducted to evaluate which parameters involved in the sewer construction and renovation (parameters in grey in Table 2) have the highest influence on the different environmental impact categories. The parameters included in the sensitivity analysis are the type of pipe material (PVC, HDPE, precast concrete and reinforced concrete), diameter of the pipes (ranging from 20 to 160 cm), transport distances for materials (ranging from 0 to 100 km) and the characteristics of the working area (location, type of soil and asphalt placement). Special emphasis was put in analyzing the influence of pipe renovation, which is directly related to the life span of the materials. In the analysis, variability related to the life span of pipes was included. For PVC, an average lifetime of 25 ± 5 years was assumed. For HDPE, a lifetime of 40 ± 10 years was considered, and finally, for precast concrete and reinforced concrete pipes, a lifetime of 70 ± 20 years was assumed. Even though pipe suppliers normally specify longer life span ranges, construction companies and water agencies experience shorter life spans in practice (Blosser et al., 2003). Hence, the ranges assumed in this paper were defined after personal communication with the construction company Voltes S.L.U. (Catalonia) with more than 60 years of experience in the field. Precast concrete and reinforced concrete pipes have the same weight. Certain materials that are used, such as ductile iron, or pipe configurations, such as oval pipes, were not considered here. Finally, transportation was considered for the environmental analysis but not for the economic analysis.

With regards to renovation, the excavation process was considered as the excavation of compact soil. In addition, the energy consumed during pipe extraction from the trench was considered to be the same as during its laying. Additionally, during pipe extraction and laying during renovation, granite sand losses of 10% were considered. Finally, it was assumed that concrete pipes and excess soil are disposed of in landfills, located at 30 km., whereas plastic pipes are incinerated (a process that involves energy recovery).

2.2.2. Inventory analysis

The inventory was carried out following the steps identified in Figure 4. Comprehensive life cycle inventories for sewers construction and renovation were obtained after interviewing construction experts and reviewing sewer construction budgets from the Catalan company Voltes S.L.U. (Catalonia). The construction budgets include in detail the amount of resources (materials, energy, machinery, etc.) required to execute the work. The public database BEDEC from the Construction Technology Institute of Catalonia (Banc BEDEC, accessed in August 2013) was also used to obtain detailed information of each material or element (a pipe is for instance an element included in the database). The Banc BEDEC database supplies technical and economic information regarding all kind of elements used in the construction market. It includes detailed information of 2026 construction items including prices (before taxes). For example, the database provides information from a “concrete pipe” of a specific diameter. The information includes the weight and the price per unit (in this case, linear meter). Since concrete pipes are heavy, the database also adds the right handling machinery, in this case a crane, assuming the cost of the rental, the estimated time of use of the machinery and the diesel consumption per hour.

The calculations related with the trench characteristics and the volumes to be excavated and backfilled were estimated using the guidelines proposed in “Installing pipes for distribution, irrigation and sanitation according to current legislation” (Adequa-Grupo Uralita, 2007). Table 1 shows the rules used to calculate the width of the trenches, and Figure 2 provides guidance on to calculate the depth of the trenches.

[place Table 1 in here]

2.2.3. Environmental impact assessment

The types of materials and energy sources from the inventories were matched to their corresponding equivalents in the Ecoinvent database (Weidema et al., 2013). The potential environmental impacts were calculated through the use of LCIA characterization factors related to four impact categories from ReCiPe (H) 1.09 (Goedkoop et al., 2013). The climate change (CC) category (measured as emissions of CO_2equivalent) evaluates the emission of greenhouse gases that capture part of the irradiation reflected on the earth from the sun, which increases the temperature of the surface. The human toxicity (HT) category (measured in kg 1.4-dichlorobenzene (DB) equivalents) takes into account the environmental persistence and accumulation in the human food chain and toxicity of toxic substances related to human activities. The particulate matter formation (PM) category (measured as PM10 equivalents) evaluates the emission of small particulates that can enter into the human body and negatively affect human health. Finally, the fossil depletion (FD) category (measured in kg of oil equivalent) considers the depletion of fossil fuels from hydrocarbons. All inventories used for the materials and energy production processes in this study were taken from Ecoinvent 3 (Weidema et al., 2013) except the inventories related to the materials deposition, which were taken from Ecoinvent 2.1. (Frischknecht et al., 2005).

3. RESULTS AND DISCUSSION

3.1. Inventory tool for sewer systems

To facilitate the creation of material and energy inventories and the assessment of LCA impacts for the construction and renovation of sewers, a tool that works automatically was created. This tool automates steps two to four described in Figure 4.

[place Figure 4 in here]

The tool was implemented in an Excel® spreadsheet and incorporates all parameters and options required for sewer system construction, renovation and end-of-life of sewer systems (Table 2). Once the required input data are introduced, the tool automatically estimates the material and energy inventory, the LCA impacts (CC, HT, PM and FD) and costs. The environmental impacts can be estimated either per considered materials or per considered processes. A prototype version of the tool, which is not intended to be used for commercial purposes, is provided as supplementary information.

[place Table 2 in here]

Results of the inventory analysis stage are summarized in Table S1 from supplementary information.

3.2. Environmental impact profile and costs for the initial hypothetical sewer system

The construction and renovation of a 1 km PVC pipe with a diameter of 40 cm generates environmental impacts (Figure 5). For CC the overall impact represent $3.11 \cdot 10^5$ kg CO_2 eq, for HT $5.63 \cdot 10^4$ kg 1.4-DB eq, for PM kg $5.03 \cdot 10^2$ PM-10 eq and for FD $1.14 \cdot 10^5$ kg of oil depletion (in all categories this number is the sum of the contribution of both construction and renovation phases). Renovation of the sewer has a larger impact compared with that of construction, which is 2.2 times higher for CC, 3.2 higher for HT, 1.4 higher for PM and 1.6 higher for FD (this accounts for two renovations). Except for CC, impacts from one renovation do not equal those from one construction, being larger for HT (renovation includes incineration of the PVC pipe which generates emissions of Arsenic, Barium, Manganese, Selenium and Vanadium into water, amongst others, associated with the combustion or the production of chemicals used during the incineration process) and smaller for PM and FD (e.g. 90 % of the granite sand is reused during renovation).

[place Figure 5 in here]

With regards to the construction phase (left side of double bars for construction and renovation in Figure 5), pipe laying (which also includes PVC pipes production) is the major contributor to the CC, FD and HT categories, with a 55%, 63% and 54% share respectively. Backfilling represents 44% and 42% of the PM and the HT impacts, respectively. With regards to the renovation phases, besides pipe laying, with a contribution to the impact of 52% in CC, 56% in PM and 80% in FD categories, the deposition of trench materials significantly contributes to the impacts (particularly for CC and HT, with a share of 34% and 61% respectively).

When analyzing the contribution of the processes (right side of double bars for construction and renovation in Figure 5), the production of PVC (both for construction and renovation) is the primary source of impact for CC (around 50% for both construction and renovation), FD (60% for construction and 74% for renovation) and for HT (53% share in the construction and 33% in the renovation). Trench material deposition impacts are primarily driven by PVC incineration. Diesel burned in machines is the major contributor to the PM impact category (39% contribution on the construction and 46% on the renovation) together with the production of PVC (30% for construction and 43% for renovation). Either looking at the phases or processes, the non-inclusion of the renovation phase results in underestimation of the environmental impacts between 58 and 77% depending on the category.

Figure 6 shows that the sewer pipe renovation of the initial sewer system (90,480 €) (two renovations are included) is more expensive than its construction (73,970 €). The increase of costs is related to pipe laying because pipes are changed twice during the life span of the sewer. Analyzing the different phases, it is possible to see that for construction, backfilling, which includes the price of the granite sand, machines, water used and labor force, is the most expensive phase followed by pipe laying, which includes the pipe, machines, water and labor force. In addition, during the renovation phases, pipe laying is the most expensive process followed by backfilling and excavation because only a small part of new granite sand is replaced, whereas new pipes must be acquired each time. From a life cycle cost point of view, costs for renovation should also be included in the infrastructure asset management because they are higher than that for construction. Hence, the phases contributing the most to the environmental impacts are also the most expensive ones.

[place Figure 6 in here]

3.3. Influence of different parameters on the environmental impacts

3.3.1. Influence of pipes (materials and diameters)

Different pipe materials were evaluated (PVC, HDPE, precast concrete and reinforced concrete) for diameters ranging from 20 to 160 cm (Figure 7), while maintaining the remaining characteristics of the initial sewer system. Regarding CC, PVC sewers always have a larger impact than concrete (reinforced concrete and precast concrete) and HDPE sewers. PVC results in 40 to 55% larger impacts compared with that of HDPE depending on the impact category. The large differences between PVC and HDPE are explained by their different life spans (25 years implying 2 renovations against 40 years implying 1 renovation) and because for all of the studied categories except for FD, the impact generated per kg of tube produced is larger for PVC (it is worth noting that weight for PVC and HDPE were assumed to be the same). Comparing PVC and concrete pipes, the relative differences are the largest and increase with diameter (up to 299% for the FD impact category for a 150 cm diameter PVC pipe).

[place Figure 7 in here]

For HT, two different groups of pipe materials can be distinguished. Significantly larger impacts are estimated for PVC and reinforced concrete, whereas smaller impacts are obtained for HDPE and precast concrete. Larger impacts are associated with materials production because the emissions to the air of mercury during PVC production and reinforcing steel contribute mostly to the HT impact. This difference becomes more evident as the diameter increases. For small diameters (< 50 cm) the difference between these groups is less than 100% and for large diameters (> 90 cm) increases up to 150%.

For PM, reinforced concrete has the highest impact followed by PVC, precast concrete and HDPE. Differences between PVC and reinforced concrete are constant and have a higher impact by approximately 40% for reinforced concrete. However, when comparing PVC against the other materials, differences appear with larger diameters (> 90 cm., between 134-155% for HDPE and 58-100% for precast concrete) because the impact per kg of PVC is higher than HDPE in addition to the lower life span for PVC.

For FD, there are two types of materials that follow different trends. The first type includes concrete-based pipes, and the second type is plastic pipes. Plastic sewers have a 1.5 to 3 times higher impact compared with that of concrete sewers because plastic requires energy during its production and transport phases and also includes the embedded (fossil) energy in the form of crude oil.

Overall, the obtained results show that environmental impacts are lower for precast concrete and HDPE pipes. This fact is due to the longer life of concrete and HDPE compared with that of PVC and also because the production of PVC pipes (per kg of material) has a greater impact than other materials. In terms of CC, this statement is in agreement with Du et al. (2013), where it was also shown that concrete and HDPE pipes have the lowest contribution to CC. However, Du et al. (2013) obtained higher CO_2eq emissions than the ones obtained in this study. For instance, for a ≈30 cm PVC pipe, Du et al. (2013) estimated 3600 kg $CO_2eq\cdot km^{-1}\cdot year^{-1}$ and this study obtained 2500 kg $CO_2eq\cdot km^{-1}\cdot year^{-1}$, and still Du et al. (2013) did not consider incineration which would result in even 38% higher emissions. In fact, the emission factors used in Du et al. (2013) for the production of PVC result in 19 kg $CO_2\cdot(kg\ PVC)^{-1}$ compared to 2.72 kg $CO_2\cdot(kg\ PVC)^{-1}$ applied in this study using the Ecoinvent database. In contrast to our statement, Petit-Boix et al. (2014) concluded that PVC pipes have the lowest environmental impacts. Their results differ from ours mainly because they did not include the end-of-use processes of the renovation phase. In this study incineration of PVC and HDPE pipes were modeled, and more energy is recovered during the incineration process for the HDPE pipe since it has a much higher heating value than PVC (41.84 $MJ\cdot kg^{-1}$ and 20.92 $MJ\cdot kg^{-1}$, respectively). Piratla et al. (2012) concluded as well that HDPE pipes production and installation result in lower CO2 emissions than PVC pipes.

3.3.2. Influence of transport distances

As shown in Figure S1, varying the transport distances (from 0 to 100 km) of excess materials from the construction site to landfill and from suppliers to the construction site result in less than 4% change for all impact categories compared to the initial hypothetical sewer system. The influence of PVC pipe transportation was even lower (results not shown). By looking into Table S1, it can be seen that the influence of transport distances is even lower as pipe diameter increases.

3.3.3. Site-specific characteristics

The influence of changing site-specific characteristics (soil type in construction area, asphalt placement need, and urban or non-urban setting) on the initial hypothetical sewer is shown in Figure 8. For the initial hypothetical sewer (with PVC pipes) changing from compact to soft soil does not make a difference on any of the impact categories, whereas changing to rocky soil increases the impacts between 9 to 34 % depending on the impact category. With increased diameter size (80 and 140 cm) the percentage of change decreases because the contribution of the tube laying and backfilling increases. When covering the trench with asphalt the impacts increase by around 20% for CC and HT, and up to 35% and 55 % for PM and FD, respectively. Again, this influence decreases as the diameter increases. The environmental burden from constructing the sewer on an urban or a non-urban setting does not show a significant difference.

[place Figure 8 in here]

3.3.4. Pipe deposition

Considering the disposal of pipes at the end of their life enables the inclusion of both the additional impacts of disposal (e.g., transport, incineration) and also the recovery of feedstock energy from plastic material. The effect of taking into account the disposal process (incineration for PVC and HDPE with electricity production and a specific landfill for construction materials for precast concrete and reinforced concrete) is shown compared with the exact same sewer but without considering disposal (0%) (Figure 9).

[place Figure 9 in here]

As shown in Figure 9, including the disposal process adds between 28 to 71% of the impact to CC for plastic pipes, which is mostly due to CO_2 emissions from incineration. The partial recovery of electricity from the heating value of plastic materials in incineration does not offset the negative impacts from incineration emissions. For HT, the additional impact of disposal is even more pronounced, with an increase of 74-147% for PVC compared with the baseline. For particulate matter and FD, including the disposal phase is less important and adds only 1-8% for PVC to the impacts, and in the case of HDPE, the impact decreases between 5 and 15% because fewer resources are used and more energy is obtained in the HDPE incineration. For concrete-based materials, the impact of including disposal is marginal (< 5%) for all four impact categories, which is essentially because disposal only includes additional transport to the landfill and no subsequent emissions or energy recovery.

3.3.5. Influence of life span

Given the defined life span ranges for each material, the selection of the highest or the lowest values (see section 2.2.1.) (compared to the average value assumed) greatly affects the obtained results (Figure 10). PVC increases between 20% and 40% of the impact depending on the category when using the lowest life span. The increase is even larger for HDPE, between 40 and 60% (but still lower absolute values compared to PVC pipes). For concrete materials the selection of the highest life span value represents a decrease in the environmental impacts between 40 and 50% depending on the category. The combination of the effect of the diameter together with the life span results in differences lower than 12 % (differences for each studied characteristic between the black, light grey and dark grey). This means the influence of the selection of life span is large no matter the pipe diameter.

[place Figure 10 in here]

3.3.6. Influence of including renovation or not

The results presented in section 3.2 already indicate that including renovation for PVC pipes has a significant contribution. Table S2, including a summary of all the sensitivity analysis, shows how the non-inclusion of renovation would underestimate the impacts from 40 to 80% for different pipe materials and diameters.

4. CONCLUSIONS

The following conclusions can be drawn from the results presented:

- Renovation of pipes after their technical life span has expired greatly influences all environmental and cost impacts during the lifetime of a sewer system; in the initial hypothetical sewer system, the renovation has an impact between 55 to 77% to the total environmental impact depending on the studied impact.

- The environmental impacts generated during the construction are mainly associated with pipe laying and backfilling of the trench. During the renovation apart from backfilling and pipe laying also the trench deposition phase has a high influence in the results.
- In the initial hypothetical sewer system, the pipe material production process has an impact between 30 and 60% depending on the impact category for construction and between 33 and 74% for renovation.
- A proper life span selection for the pipes is crucial because the results greatly change, ranging from a reduction of the impact of 51% to an increase of 61%.
- Precast concrete and HDPE sewer construction generates lower environmental impacts in the studied categories than PVC pipes because they have a longer life span and the pipe production has a lower impact (per kg of pipe).
- Soil characteristics of the underground have a high environmental impact whereas transport distances have not an important influence.
- Final disposal of pipes affects the final results, particularly for plastic pipes, for which the environmental impacts can increase up to 69% for CC and 145% for HT.
- The influence of the pipe material and its deposition becomes more important when the pipe diameter increases.
- All calculations shown in this paper were obtained thanks to the automatic tool, which was developed to facilitate the development of material and energy inventories for the construction and renovation of sewers and the calculation of environmental impacts and costs. This tool can be easily expanded and adapted to include other processes, which might be relevant in other countries.

Upgrades of the tool could also include considering more trench filling options (with concrete), introduction of more pipe materials and diameters and also different pipe shapes besides circular pipes. The tool could also introduce information regarding pumping stations, manholes and sewer system constructive solutions different than those already considered. Another interesting upgrade of the tool would be the inclusion of different types of uncertainties in the processes considered. Still the tool has a potential to become widely applicable to estimate detailed and complete inventories and environmental impacts of sewer systems.

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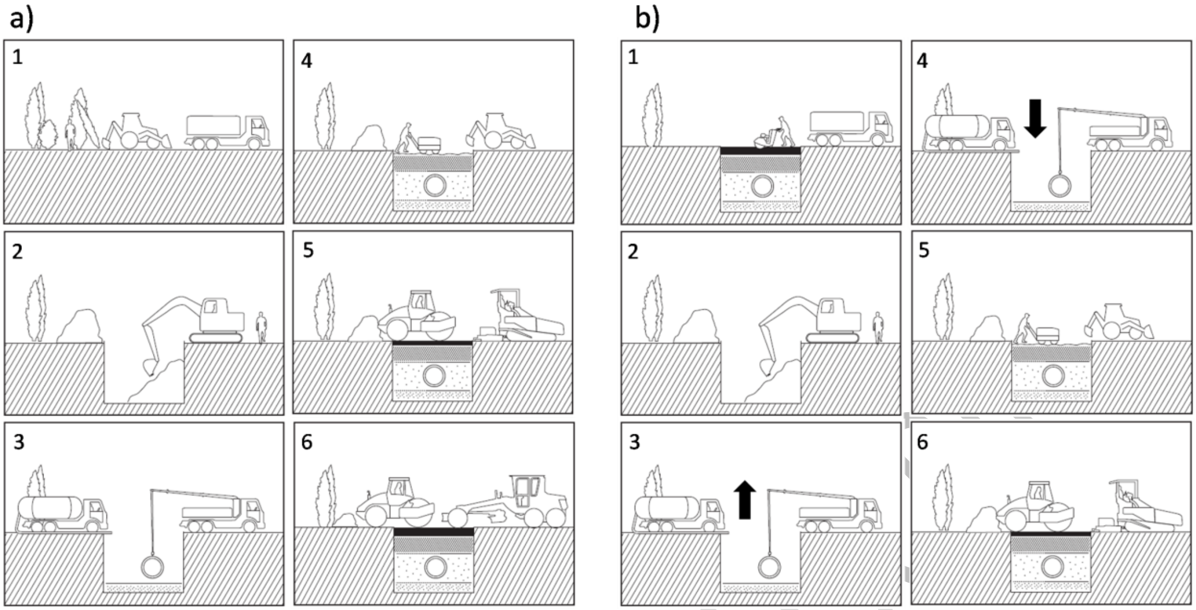

Figure 1: Illustration of the required phases for construction and renovation of sewer pipe located in a non-urban area with traffic, the figure shows the general procedure to construct a sewer pipe: a) Construction: 1) work area cleaning; 2) Excavation; 3) Pipe laying; 4) Backfilling; 5) Asphalt placement; 6) Distribution of excess soil; b) Renovation: 1) Asphalt layer breaking; 2) Excavation; 3) Pipe extraction; 4) New pipe laying; 5) Backfilling; 6) New asphalt placement.

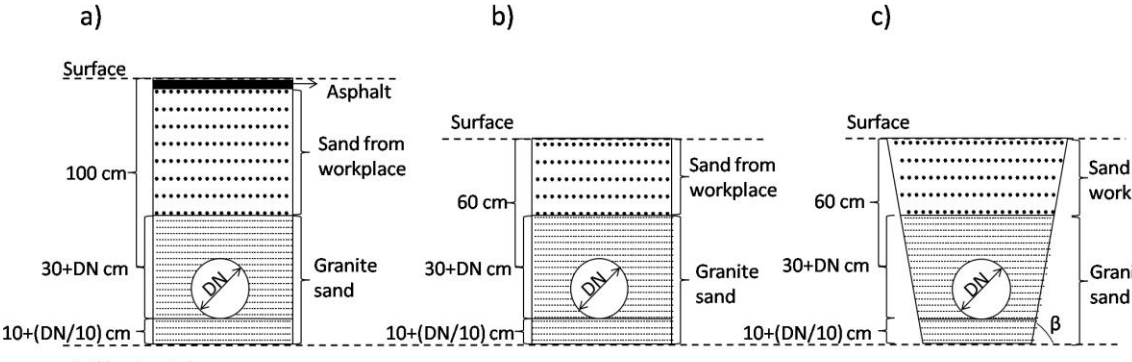

Figure 2: Rules for the calculation of the trench depth, a) with traffic in the upper part in a rectangular trench, b) without traffic in the upper trench in a rectangular trench, c) without traffic in the upper trench in a trapezoidal trench. Option B is the option used for the initial hypothetical sewer system. DN is the diameter of the pipe. β is the angle between the trench wall and the soil horizontal (β=90º rectangular trench, β<90º trapezoidal trench).

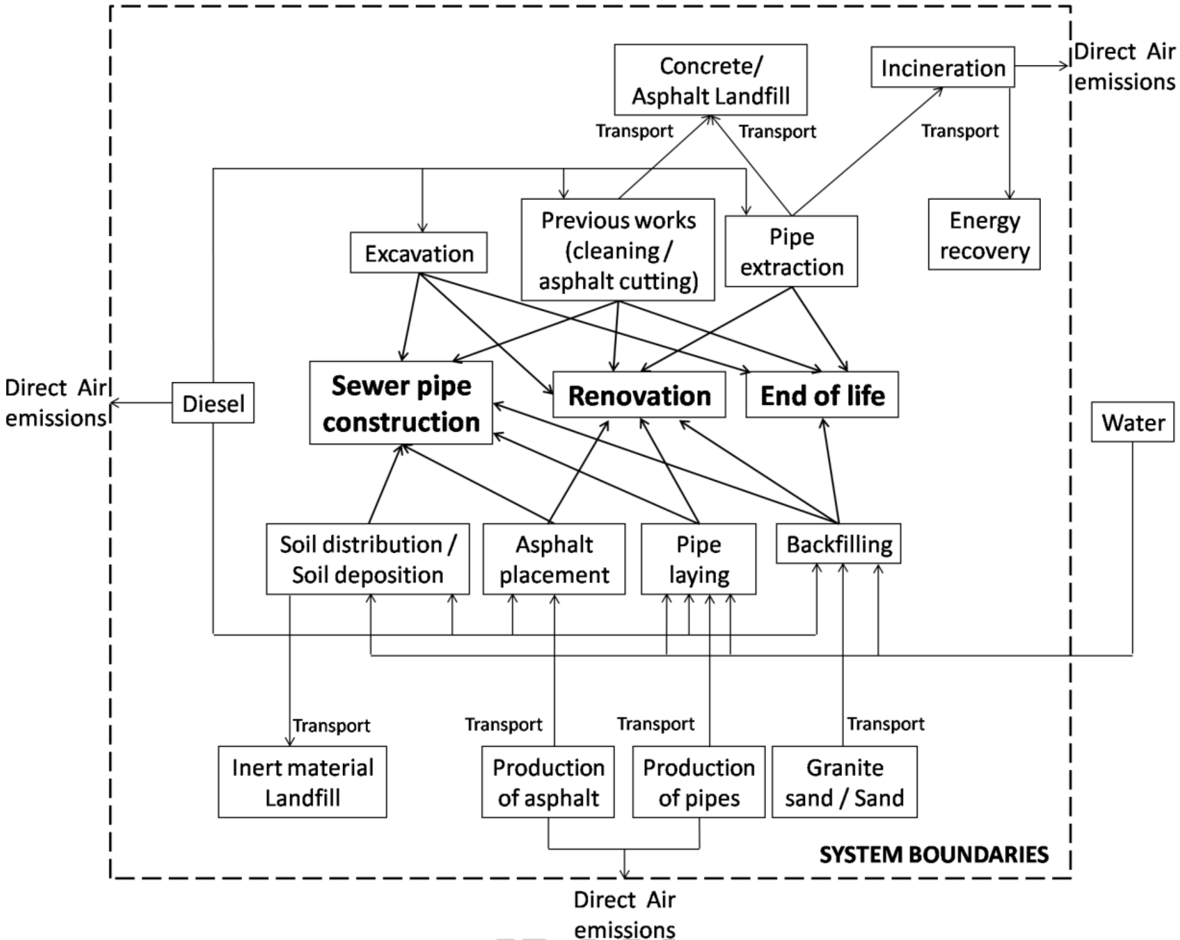

Figure 3: System boundaries, phases and processes considered.

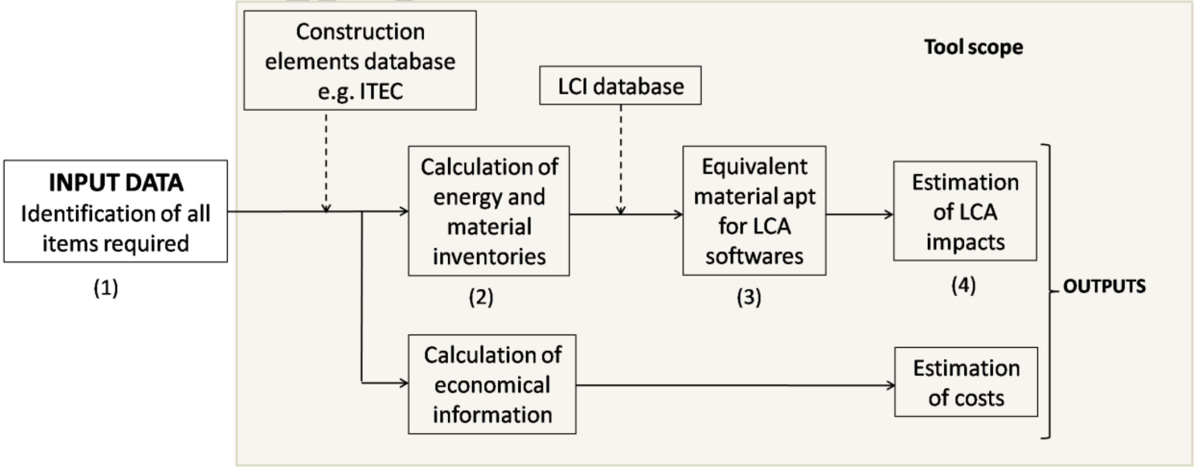

Figure 4: Tool scope and all of the necessary steps to calculate the impacts of a sewer system. The Excel®-based tool automates steps 2 to 4.

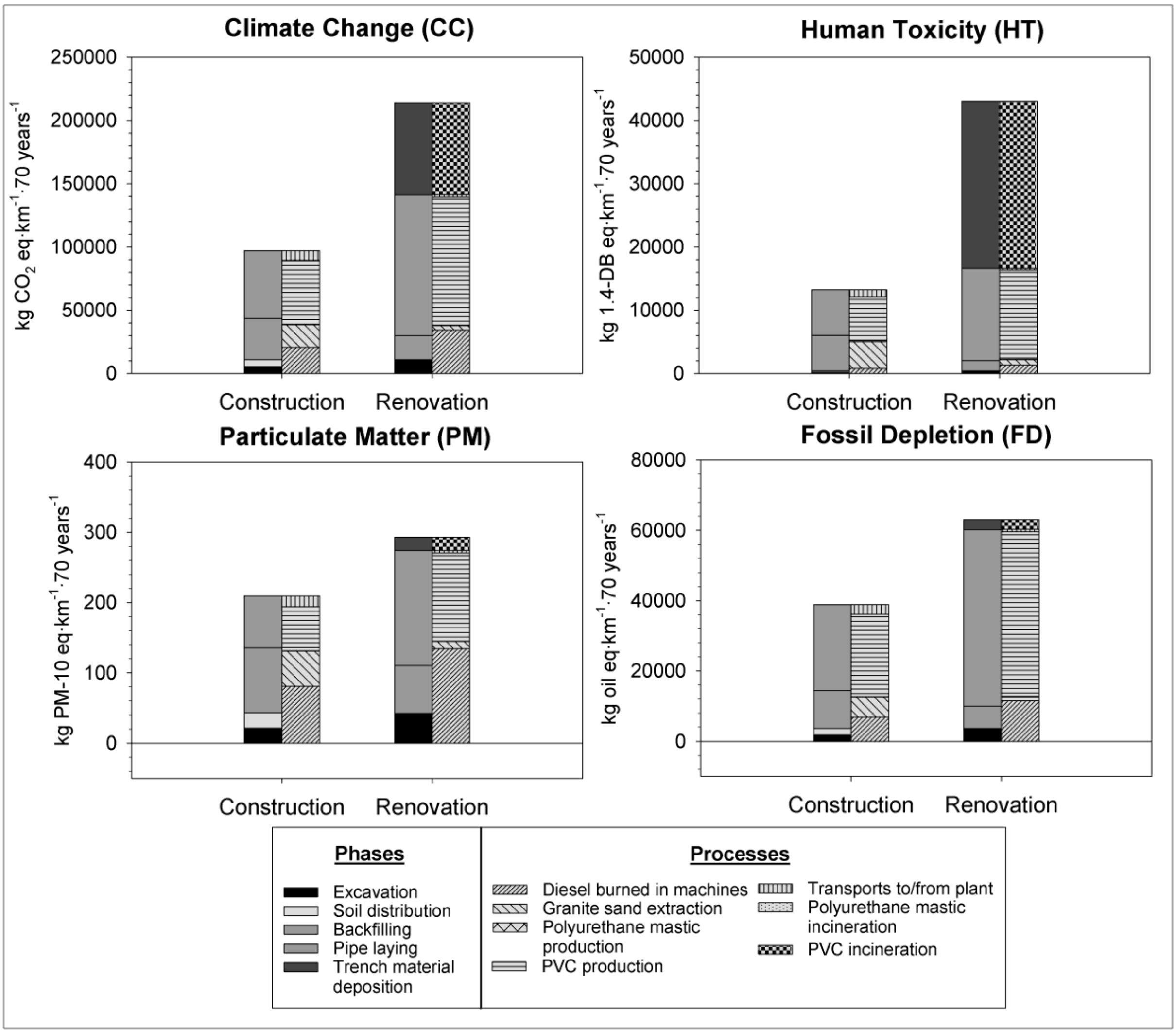

Figure 5: LCIA results for the initial hypothetical sewer system with a length of 1 km and a PVC pipe with a diameter of 40 cm (analysis includes construction and renovation). The results include a single construction and two renovations over 70 years of operation. For each impact category, the results are split into the construction and renovation phases. Left part of each bar (construction or renovation) relates to the phases and the right part of each bar relates to the processes. Total impact for each category is the sum of construction and renovation bars.

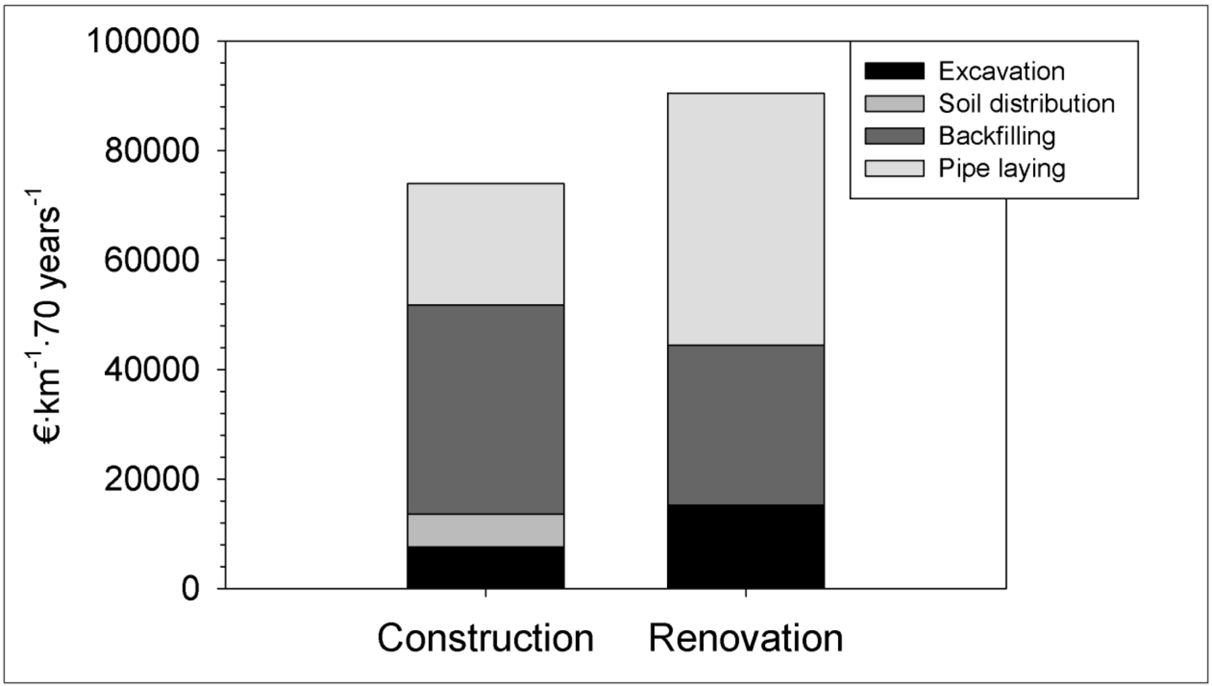

Figure 6: Costs for the different phases of the initial sewer system construction and renovation (2 renovations needed over 70 years).

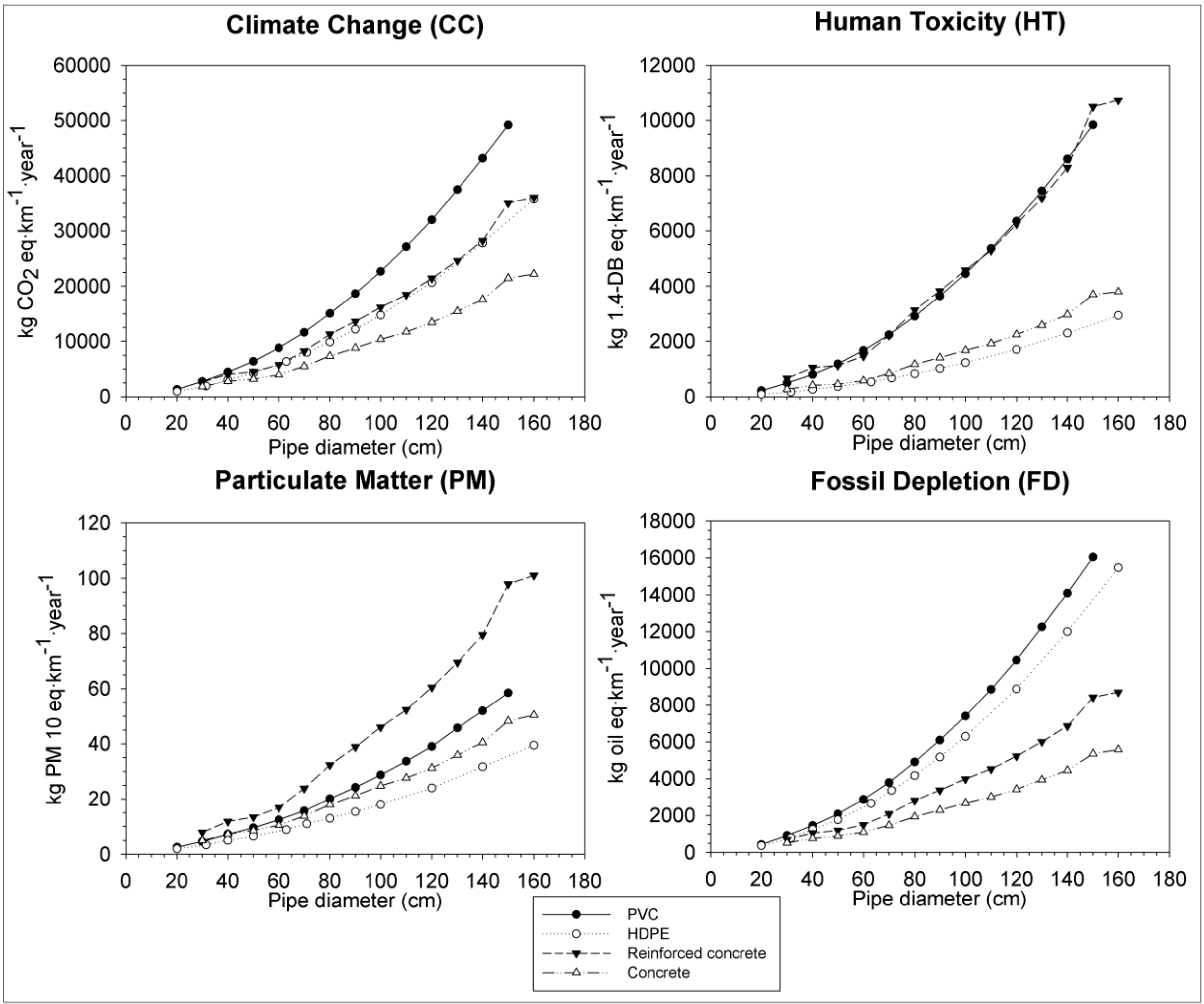

Figure 7: Environmental impacts for the construction and renovation of a 1 km sewer pipe using different materials (PVC, HDPE, reinforced concrete, precast concrete) and diameters (from 20 to 160 cm). The initial hypothetical sewer system corresponds to the PVC pipe of 40 cm diameter.

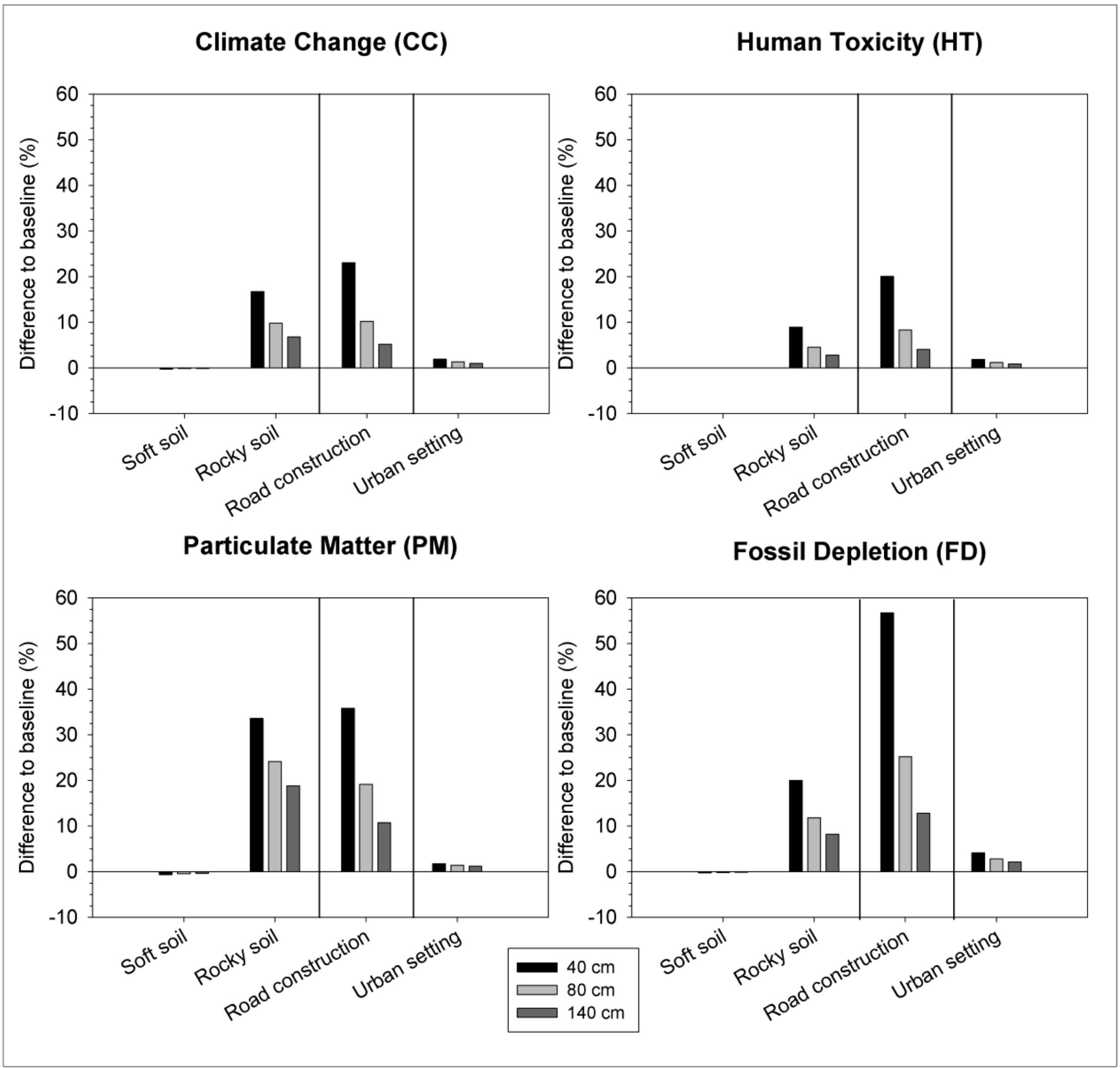

Figure 8: Influence of site-specific characteristics (soft and rocky soil vs compact, asphalt placement when a road is constructed vs no asphalt, and urban vs non-urban setting) on the environmental impacts. The impact of each site-specific characteristic is referred to a baseline, which corresponds to the initial hypothetical sewer system but with 3 different diameters (40, 80 or 140 cm).

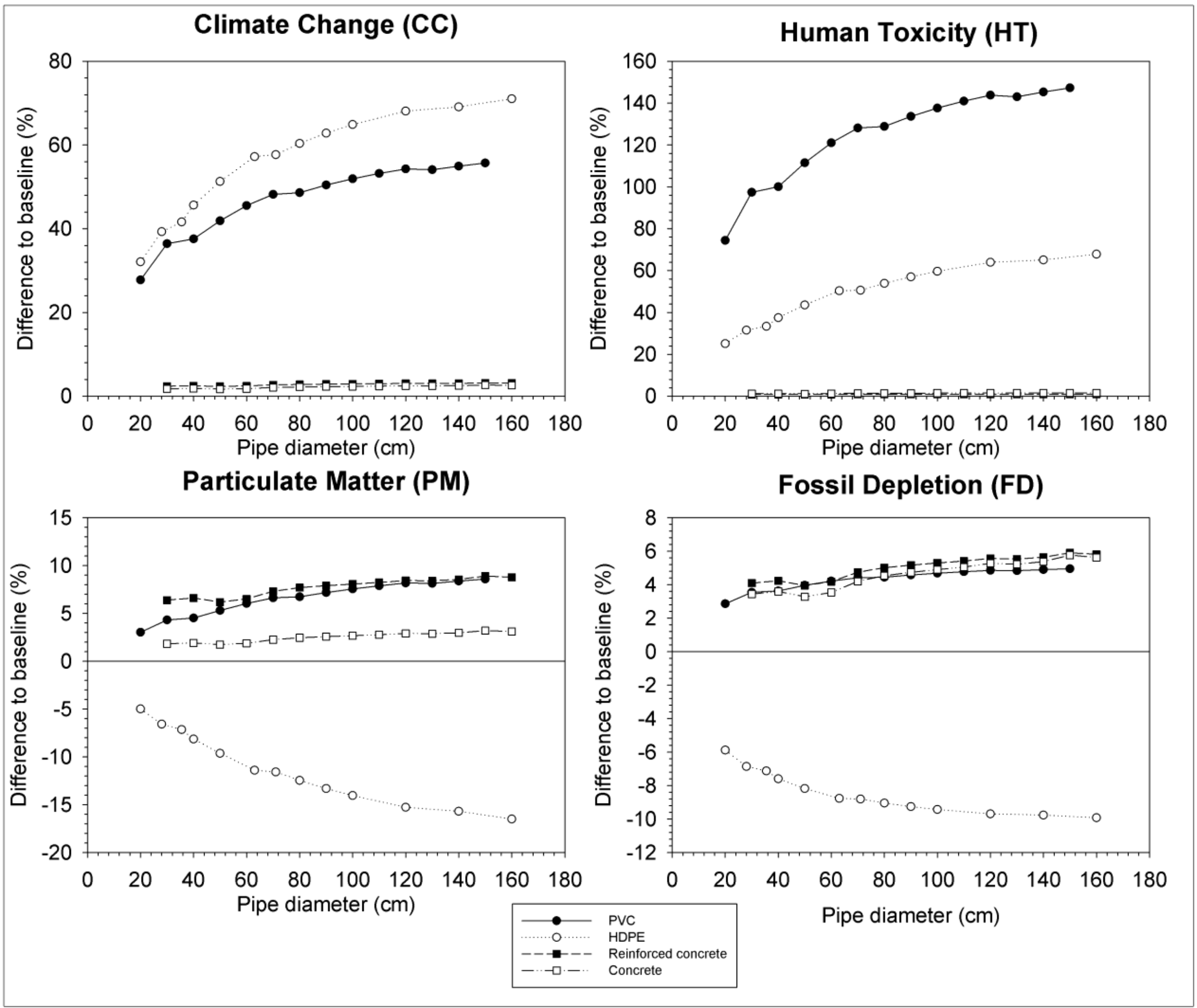

Figure 9: Effect of including deposition on the LCIA of a 1 km sewer pipe (positive percentages mean increased impacts whereas negatives percentages correspond to decreased impacts). Different materials and diameters are evaluated. Baselines (no deposition included) are different for each material and pipe diameter and the percentages of change after including deposition are calculated compared to these baselines.

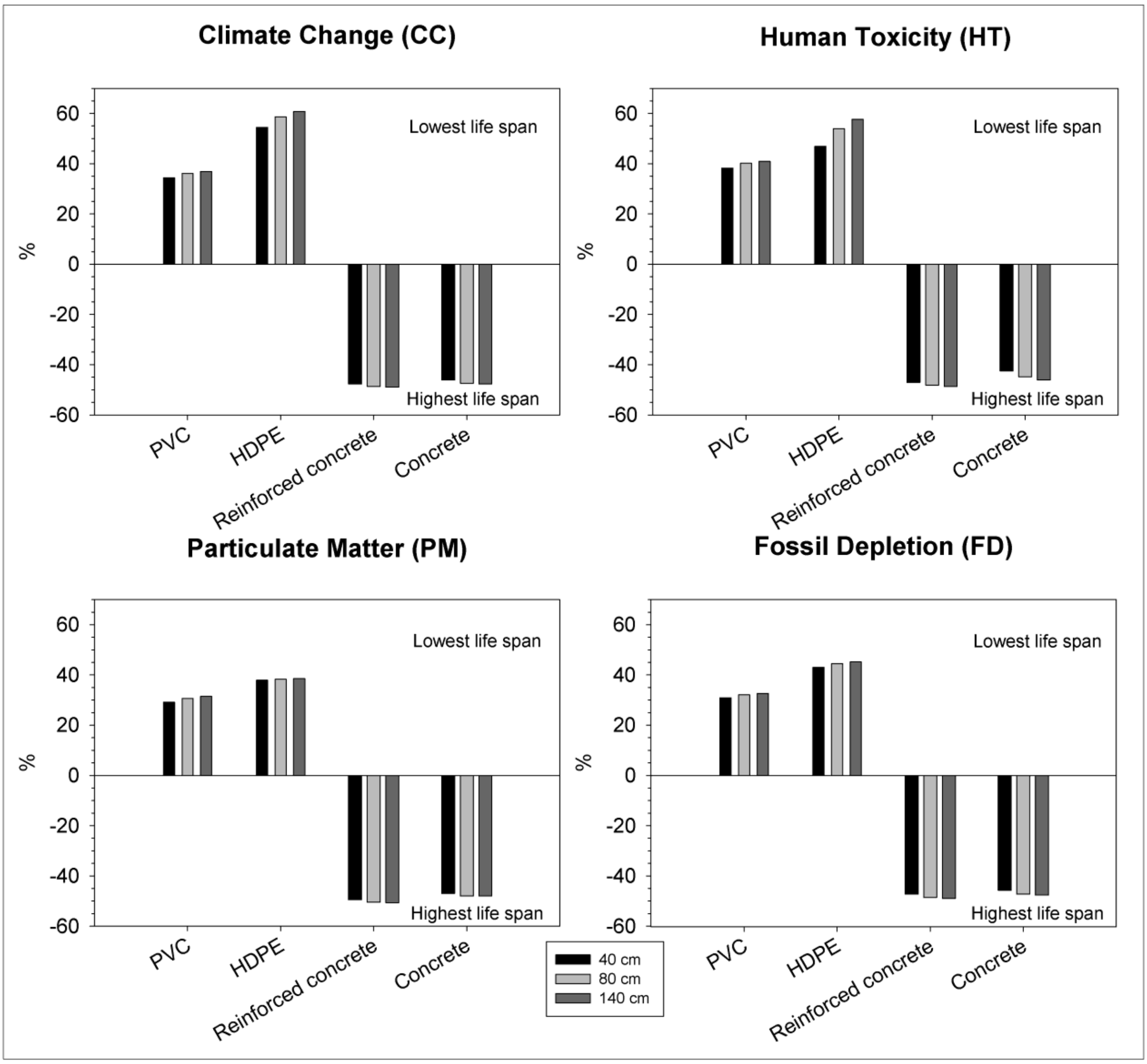

Figure 10: Influence of the pipe material life span to the environmental impacts from the construction and renovation of 1 km sewer system. The results are obtained after calculating the impacts on the initial sewer system typology and changing from the average life span (the baseline) to the highest and the lowest value (results show the maximum difference obtained).This evaluation is conducted separately for each pipe material (except for the material and its corresponding life span the remaining characteristics from the initial sewer are applied).

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Table 1: Rules to calculate the trench width at the bottom. Trench width has to be large enough to place the tube and has space to work. The trench width depends on the pipe diameter (because more extra space will be needed as bigger is the diameter), the necessity to underpin the trench or not and the angle between the trench wall and the soil horizontal. Information from Adequa-Grupo Uralita, 2007.

Pipe diameter (mm)	Minimum trench width (OD + x), meters		
	Underpinned trench	No-underpinned trench	
		β > 60º	β ≤ 60º
≤ 225	OD + 0.40	OD + 0.40	
> 225 to ≤ 350	OD + 0.50	OD + 0.50	OD + 0.40
> 350 to ≤ 700	OD + 0.70	OD + 0.70	OD + 0.40
> 700 to ≤ 1,200	OD + 0.85	OD + 0.85	OD + 0.40
> 1,200	OD + 1.0	OD + 1.0	OD + 0.40
OD is the outside diameter of the pipe in meters. β is angle of the no-underpinned trench wall measured from the horizontal.			

Table 2: Parameters, options and their effects considered in the inventory tool for the sewer system construction, renovation and end-of-life. All the parameters considered in the sensitivity analysis performed in the work are colored in grey.

Parameter	**Options considered**	**Phase affected / Practical effects**
Location	Urban	Excavated soil to landfill
	Non-urban	Distribution of excavated soil near the construction site
Work area cleaning	Yes	Cleaning may be required to prepare the surface for further work, which will double the trench surface in the calculation
	No	
Traffic	Yes	If there is a road above the trench, it is necessary to construct deeper trenches and install asphalt
	No	
Trench underpinning	Yes	For urban area, underpinning is considered in soft and compact soils
	No	

		For non-urban area, underpinning is not considered because it is preferable to construct trapezoidal trenches
Surface to be cleaned before the work	Automatic calculation	Is calculated automatically considering 2 times the trench surface in the soil surface
Surface to be underpinned	Automatic calculation	Is calculated automatically considering the surface of the trench walls
Pipe material	PVC	Each material has different characteristics (e.g., weight, longevity)
	HDPE	
	Reinforced concrete	
	Concrete	
Pipe diameter	From 20 to 250 cm	Depending on the material
Trench shape	Rectangular	Angle between trench and soil $\beta=90°$
	Trapezoidal	Angle between trench and soil $\beta<90°$
Angle	Between 90º and 30º	The angle selected determines the trench shape
Trench length	Case specific	Determines the length of the trench and useful to calculate the volume of excavation
Type of soil	Soft	Depending on the hardness of the material to be excavated, more diesel is consumed during excavation. In addition, rocky soil must be transported to the landfill for disposal
	Compact	
	Rocky	
Distances from material distributors	Case-specific	Transport distances between the workplace, distributors and deposition facilities can be defined
Deposition of the trench material	Yes	To calculate the environmental impact of the deposition of the trench material after its use and when the renovation is not included in the analysis, renovation automatically includes the deposition of the old one
	No	
Renovation inclusion	Yes	Renovation of the sewer includes regular exchange of pipes after their life span and all relevant work related to it
	No	
Years of operation	Case specific	Total time frame for the analysis in relation to the lifetime of the pipes will determine the number of renovation events
Nº of renovations	Automatic calculation	Is calculated automatically when the renovation is considered. The calculation depends on the years of operation and the tube material selected, each tube material has different life span
Distances to deposition treatments	Case specific	Distance in km between the workplace and the deposition infrastructure