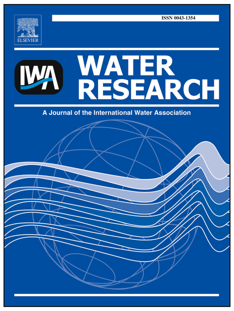

Using a detailed inventory of a large wastewater treatment plant to estimate the relative importance of construction to the overall environmental impacts

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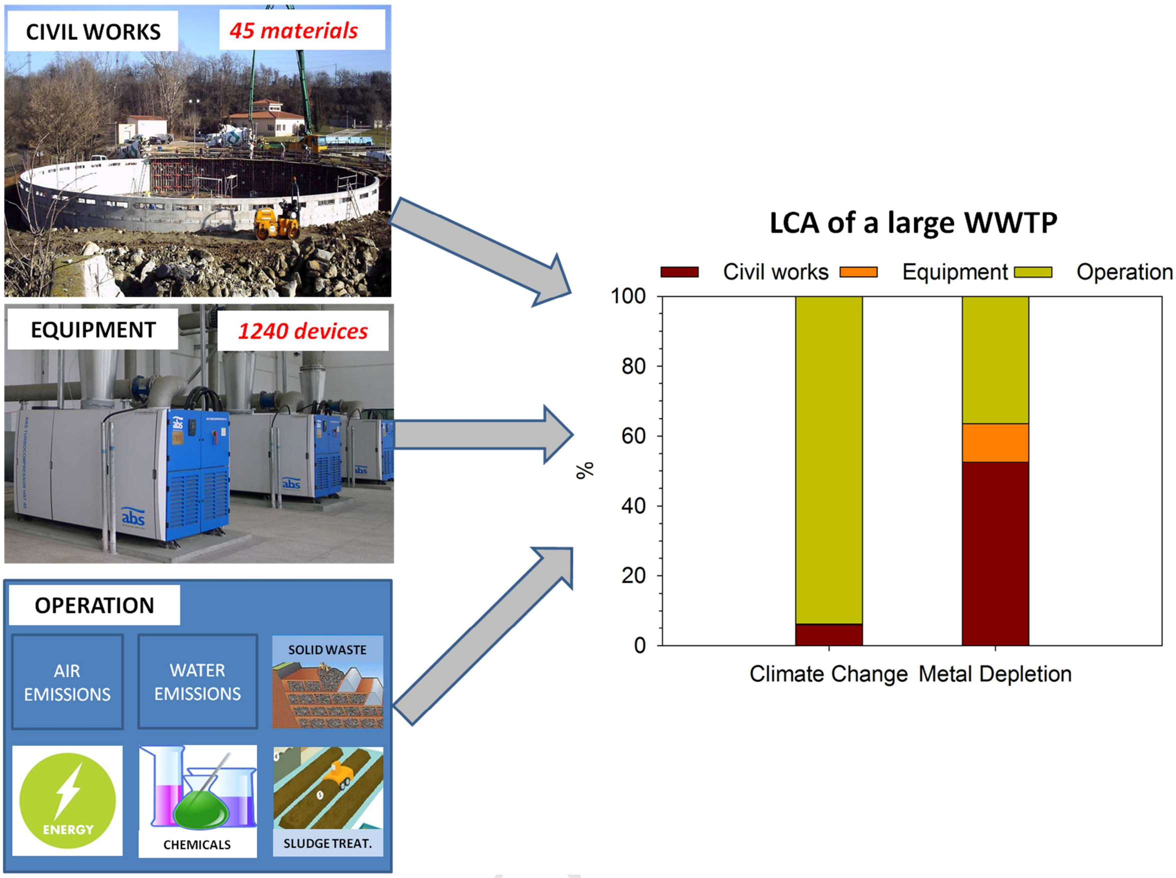
CIVIL WORKS
45 materials
EQUIPMENT
1240 devices
OPERATION
AIR EMISSIONS
WATER EMISSIONS
SOLID WASTE
ENERGY
CHEMICALS
SLUDGE TREAT.
LCA of a large WWTP
Civil works
Equipment
Operation
%
100
80
60
40
20
0
Climate Change
Metal Depletion

Using a detailed inventory of a large wastewater treatment plant to estimate the relative importance of construction to the overall environmental impacts

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Abstract

The aim of this work is to quantify the relative contribution to the overall environmental impact of the construction phase compared to the operational phase for a large conventional activated sludge wastewater treatment plant (WWTP). To estimate these environmental impacts, a systematic procedure was designed to obtain the detailed Life Cycle Inventories (LCI) for civil works and equipment, taking as starting point the construction project budget and the list of equipment installed at the Girona WWTP, which are the most reliable information sources of materials and resources used during the construction phase. A detailed inventory is conducted by including 45 materials for civil works and 1240 devices for the equipment. For most of the impact categories and different life spans of the WWTP, the contribution of the construction phase to the overall burden is higher than 5% and, especially for metal depletion, the impact of construction reaches 63%. When comparing to the WWTP inventories available in Ecoinvent the share of construction obtained in this work is about 3 times smaller for climate change and twice higher for metal depletion. Concrete and reinforcing steel are the materials with the highest contribution to the civil works phase and motors, pumps and mobile and transport equipment are also key equipment to consider during life cycle inventories of WWTPs. Additional robust inventories for similar WWTP can leverage this work by applying the factors (kg of materials and energy per m^3 of treated water) and guidance provided.

Keywords: Civil works, equipment, LCA, life span, WWTP, detailed inventory

1. INTRODUCTION

Wastewater treatment plants (WWTPs) are designed to reduce the impact of wastewater generated in urban systems before discharging it to the receiving water bodies. Despite their beneficial contribution to the environment, they also generate environmental impacts during their construction, operation and dismantling. Life Cycle Assessment (LCA) is the most commonly used methodology to evaluate the global environmental impacts of WWTPs. All impacts produced throughout a WWTPs' lifetime, from their construction and operation until deposition or recycling, are included in the assessment, however not all are included systematically.

This paper focuses on the construction phase, including both civil works and equipment, as we believe that it is a stage which has been understudied (Remy and Jekel, 2008). As an indication, in the review of LCA application to WWTPs from Corominas et al. (2013) only 22 studies (out of 45 reviewed) included the construction phase and only 15 provided their own inventories. Some studies report a contribution of construction to the overall WWTP impacts lower than 5% (e.g. Emmerson et al., 1995; Vlasopoulos et al., 2006). Besides, coming up with detailed own inventories is tedious and time consuming. This persuades some researchers/practitioners to perform detailed inventories. A potential solution (as applied in Foley et al., 2010) is the estimation of the volume of reinforced concrete which is then used as a multiplier for the estimation of other construction phase materials taking as a reference the inventories provided by Ecoinvent (Doka et al., 2007). In the case that construction is included, a minority of studies include equipment with limited information (e.g., Tillman et al., 1998; Lundin et al., 2000; Machado et al., 2007; Ortiz et al., 2007; Stokes et al., 2010; Foley et al., 2010; Risch et al., 2015), the rest only take into account civil works. In general, data on materials use (concrete, steel, etc.) can be collected but information on the utilities (e.g. energy consumption of constructing vehicles) is missing. In spite of these difficulties, according to us, we should account for both civil works (production of materials, transports from factory to workplace and combustible consumed) and also equipment (i.e. thousands of devices, including diffusers, pumps and blowers), which has to be replaced several times during the life span of the WWTP. The low level of detail of construction inventories published so far and the large number of assumptions normally taken questions the validity of the estimates of the share of construction to the overall environmental impacts of WWTPs.

Hence, the objective of this work is to estimate the relative importance of construction to the overall environmental impacts of a large WWTP thanks to the development of a detailed inventory. The main novelty compared to previous published work lies in the provision of detailed inventories for civil works (including 45 different materials) and equipment (1240 devices), operation and dismantling. The inventory is modular as the WWTP has been divided into 5 units: pumping & pretreatment, primary treatment, secondary treatment, sludge line and deposition, and buildings and services (offices building and exterior landscaping).

The paper is organized as follows. First, in the methodology section, a systematic procedure to obtain detailed Life Cycle Inventories for civil works and equipment is introduced. Then this methodology is used to obtain the construction inventories for a real WWTP. In the results and discussion section, first, the contribution of the WWTP construction (civil works and equipment) and operation to the overall impact are compared, including a sensitivity analysis to evaluate the relevance of the WWTP life span as well as an uncertainty analysis of the inventories of the civil works, equipment and operation. Second, the contribution of the construction (civil works and equipment), including also its dismantling, and operation to the impact for each operational unit and impact category is analyzed. Third, a cumulative effect to the overall impact of the civil works, equipment and operation for each operational unit and resources consumed (material, energy, transport) is shown. Finally, a set of simplifications in the construction inventory are evaluated to provide guidance to LCA practitioners.

2. METHODS

2.1. Procedure followed to obtain a detailed construction inventory

Detailed inventories for civil works includes the following steps (Figure 1): (1) Obtain the construction budget for the WWTP. In the budget, all elements needed for civil works (e.g., excavations, handrails, concrete, etc.) are listed, along with the price and the amount of each one. (2) Then, all these elements in the budget are identified and grouped in a simplified list (e.g., excavation of a representative type of soil, a representative type of concrete, etc.). (3) Once all elements of the budget are identified and grouped, it is necessary to search for equivalent elements in a specialized constructive database of reference (in our case the local database Banc BEDEC, which is used by constructors to make their budgets). This database provides all the necessary information about materials and energy consumed to build a unit of each element. (4) Finally, the material and energy inventories are calculated by relating the elements obtained from the construction budget to the equivalent elements of the reference database.

(FIGURE 1)

The procedure for equipment is as follows: (1) Obtain the list of equipment from the equipment maintenance plan or, if it is not available, using as-built documents. (2) The equipment is characterized and organized in classes. (3) Obtain the environmental product declarations (EPDs) of each class of equipment. In the EPDs, the material and energy needed for the manufacturing of each equipment are recorded. Sometimes, specific EPDs are not available, in which case it is necessary to deduce information from similar elements of each group. (4) Obtain the inventory, relating the information from the EPDs with the list obtained in the classification of the equipment.

Five WWTP units were considered in the case study: (1) pumping + pretreatment, (2) primary treatment, (3) secondary treatment, (4) sludge line and deposition, and (5) buildings and services. Table 1 provides a description of the elementary processes considered for each operational unit considered in this work. The procedure was applied to obtain detailed inventories for each one of these units of the WWTP.

(TABLE 1)

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.

2.2.1. Goal and scope definition

The goal was to perform an LCA of the Girona WWTP, considering the construction of the plant (civil works + equipment), the operation and dismantling, and making an individual analysis for the five WWTP units. The functional unit of the study is 1 m^3 of treated wastewater assuming that the WWTP is working at full capacity. In fact, WWTPs are designed and constructed to serve a specific capacity. However, the treated flow does not always match with the design flow. We assumed the lifetime of the WWTP to be 20 years (Renou et al., 2008) whereas the lifetime of the equipment was 15 years (Lundin et al., 2000). The sensitivity of the lifetime of the WWTP on the LCA assessment is addressed in a sensitivity analysis. Savage values for the equipment are considered when the life spans of the WWTP and of the equipment do not match.

The studied WWTP is located in Girona (Catalonia, NE of Spain). It treats the wastewater from the main city and different nearby towns located around the WWTP, before the effluent is discharged into the Ter River. The plant has a capacity of 206,250 population equivalents (PE), which corresponds to a design flow rate of 55,000 $m^3 \cdot d^{-1}$. However, in the year 2013 the WWTP of Girona treated on average 42,000 $m^3 \cdot d^{-1}$. The water line consists of a Modified Ludzack-Ettinger (MLE) configuration with biological removal of organic matter and nitrogen and chemical removal of phosphorus. The sludge line consists of thickening, anaerobic sludge digestion with electricity production from the biogas, and sludge dewatering. The dewatered sludge is sent to a nearby composting plant. The composting plant is a private installation located 20 km away from the WWTP, and it treats not only the sludge from the WWTP but also other organic residues from other facilities. Figure 2 shows a scheme of the WWTP with a separation of each analyzed operational unit and an indication of the operational data used to perform the LCA of the operation.

(FIGURE 2)

Pumping and pretreatment includes five pumps, two channels that are 16 meters long, two sieves, screening and grease separation. Primary treatment has three primary settlers, each with a total capacity of 412 m^3. Secondary treatment consists of three different reactors with a total capacity of 29,620 m^3 and three settlers, each with a capacity of 5,027 m^3. The sludge line includes two thickeners of 16 m of diameter, two primary digesters with a 3,432 m^3 volume, two secondary digesters with an 814 m^3 volume, two dewatering devices and a cogeneration device.

The system boundaries (Figure 3) consider the WWTP's construction, operation and dismantling. The production of all materials (and their transport) and energy used to build the WWTP (civil works + equipment) are accounted. The dismantling is considered in this study for the most abundant materials for both civil works and equipment, assuming that concrete and reinforced concrete are disposed at a landfill for inert waste, 91% of metals are recycled (Sansom and Avery, 2014) and 25% of plastics are recycled, 34% of plastics are incinerated with electricity recovery and the rest disposed in a landfill (Plastics Europe, 2012). Operation includes the electricity and chemicals consumed, the gases and water emissions from the WWTP to the environment, the deposition of residues from the pretreatment and primary treatment of the WWTP (solid residues, sand and greases), the sludge composting (but not its application in agriculture) and the electricity produced. Transports from suppliers to the WWTP during the construction and operation phases are considered as well. The construction of the composting plant is not within the system boundaries.

(FIGURE 3)

2.2.2. Inventory analysis

The procedure described in section 2.1. has been applied to obtain the construction inventories of each of the five WWTP units in terms of materials and energy (Table 2). Hence, for all WWTP stages (pre-treatment, primary treatment, secondary treatment, sludge line, buildings and services) we have accounted for materials and equipment. A summary of the construction inventory can be found in Table 2. 45 different types of materials have been used in the construction of the WWTP of Girona (see Table S-1 from supporting information for a complete material inventory). The WWTP has 1240 devices, including large equipment (e.g. blowers, pumps, motors, mixers, heat exchangers, compressors, diffusers) and small equipment (e.g. valves, gates, probes). Tables S-2a and S-2b lists all the devices and corresponding materials for all equipment installed per operational unit while section 1 in Supplementary Information details how inventories have been performed for motors and pumps. Tables S-3 and S-4 and section 1 in supplementary information provide independent inventories for all pumps and motors typically existing in WWTPs (which can be directly applied to other studies). Transports have been estimated considering the weight of the materials and assuming an average distance of 40 km.

Table 2 also includes the inventory of the operational phase. That information has been provided by Trargisa S.A., the company that manages the Girona WWTP. The chemicals used in the WWTP are iron chloride, sodium aluminate, polyelectrolyte, antifoaming and antioxidant. For iron chloride the correspondence in the Ecoinvent database has been used. For sodium aluminate no equivalent has been found in Ecoinvent, and hence we have created our own process using technical information on the chemical production. For chemicals with no technical information available an alternative similar chemical has been selected from the

Ecoinvent database. Acrylonitrile is the proxy for polyelectrolyte and silicon product is the proxy for antifoaming and antioxidant. The composting process used in this assessment is the one described by Remy (2010), which provides inventory data tailored to current composting processes (more recent than the processes available in the Ecoinvent database). The direct emissions of greenhouse gases from secondary treatment, from biogas combustion and from the degradation of the organic matter and nutrients emitted to the river, have been estimated applying the factors from Foley et al. (2010), which are 0.01 kg N_2O-N/kg N denitrified in secondary treatment, 16.02 gCH_4/Nm^3 biogas and 0.73 g N_2O/Nm^3 biogas from biogas combustion, and 0.025 kg CH_4/kg COD discharged to the river and 0.0025 kg N_2O-N/kg N discharged to the river.

(TABLE 2)

The factors provided in Table 2 (kg of materials and energy per m^3 of treated water) can be reused to develop robust inventories for the construction, operation and dismantling of treatment works similar to the Girona WWTP.

2.2.3. Environmental Impact Assessment

The types of materials, energy sources and emissions from the inventories have been matched to their corresponding equivalents in the Ecoinvent 3 database (Weidema et al., 2013). The potential environmental impacts have been calculated through the use of LCIA characterization factors related to a sub-set of impact categories from ReCiPe (H) 1.13 (Goedkoop et al., 2013). We have included climate change (CC), ozone depletion (OD), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), metal depletion (MD) and fossil depletion (FD). All inventories used for the materials and energy production processes in this study have been taken from Ecoinvent 3 (Weidema et al., 2013). The assessment has been conducted using SimaPro 8.3.0.0.

2.3. Sensitivity and uncertainty analysis

One of the most influential factors in the LCA of WWTPs is the selection of the life span (Risch et al., 2015). A sensitivity analysis has been conducted to evaluate the influence of the selection of the life span of the WWTP to the environmental impacts. Hence, besides the base case of 20 years of life span, we have evaluated as well 10 and 30 years life span.

Uncertainty analysis has been applied to analyze the variability of results due to the variation of uncertain input parameters over their whole domain of uncertainty, using the Monte-Carlo engine in Simapro. We have assumed an uncertainty of 13% for civil works which corresponds to the “unexpected issues” item in the execution budget of the Girona WWTP. This 13% covers the uncertainty related to the execution of the project given a certain budget, and does not account for possible sources of variability that one could find in other case-studies. Uncertainty has been only assessed on the amount of material used for the machinery with the highest influence on the impact (i.e. pumps and motors). The uncertainty range has been defined separately for pumps and motors after compiling EPDs from different vendors and conducting a linear regression between the usage of materials and the power (see section 2 and Tables S-5 and S-6 of supplementary information for further details on the uncertainty analysis for motors and pumps). The error associated to those regressions is assumed to be the uncertainty, ranging from 10% (for large equipment) to 400% (for small equipment).

With regards to the uncertainty associated to the WWTP operation, it was addressed after evaluating the variability in the concentrations of pollutants at the influent of the WWTP, the chemicals consumption and the electricity consumption over three consecutive years. The uncertainty values were obtained calculating the mean and the maximum and minimum values of the values. In addition, we have used the factor reported in Foley et al. (2010) to include N_2O emissions (0.0003 to 0.03 kg N2O-N/kg N denitrified in the secondary treatment). Uniform probability distribution functions have been applied to all sources of uncertainty evaluated.

3. RESULTS AND DISCUSSION

3.1. Environmental impact assessment of the construction and operation of the entire plant

When assuming a life span of the WWTP of 20 years (Figure 4, middle bar for each impact category), the contribution of the construction (civil works + equipment) to the overall burden is higher than 5% for most environmental impact categories evaluated. For MD the contribution of construction is as large as 63%, with a share of approximately 52% for civil works (i. e. $2.00 \cdot 10^6$ kg, mainly reinforcing steel) and of 10% for the equipment (e.g., $4.1 \cdot 10^4$ kg of cast iron and $1.5 \cdot 10^4$ kg of steel, without considering the replacement). For HT and FD, the contribution of construction to the overall impact is approximately 16%. In the case of FD most of the construction burden comes from the production of materials (only 3% of FD relates to energy consumed during the construction phase). For CC, OD and FE, the contribution of construction represents between 5 and 10% of the overall impact. It is worth mentioning that construction contributes to FE through emissions generated during the production of materials, such as steel and concrete as well as through landfill emissions. Only for ME the contribution to the impact of civil works and equipment is less than 1%. Keeping in mind that the cut-off criteria defined in the LCA Handbook (European Comission, 2010) is

5% influence on the environmental impacts it is clear that one cannot systematically omit the construction phase in LCA studies for WWTPs of similar configuration and size of the one studied in this paper. It is worth mentioning that the inclusion of the dismantling/end-of-life of the WWTP implies recycling most of metals from the equipment. Recycling reinforcing steel would decrease the MD burden down to negligible values for construction. However, the latter is not a common practice due to the large costs involved in the separation of concrete and the reinforcing steel.

(FIGURE 4)

The results for the sensitivity analysis of the WWTP life span shows little effect on the categories CC, OD, FE, ME and FD. For HT and MD, the longer the life span is the larger the contribution of equipment to the overall environmental impacts, as replacement will be needed. In contrast, when the life span considered is 30 years, the contribution of civil works significantly decreases for the MD category.

Overall, even when accounting for uncertainty, the conclusion that construction cannot be neglected remains valid. The uncertainty related to the operation phase has a larger influence on most of the environmental impacts than the one related to the construction phase (Figure 5). The propagation of uncertainty of the emission factor of N_2O emissions has a large impact on climate change (see errors bars for operation in CC, Figure 5). The large uncertainty behind fugitive GHG emissions can change the relative contribution of construction to the overall impacts. If fugitive GHG emissions would not be considered the contribution of construction to climate change would be higher (close to 10%). The climate change results vary by 5% when propagating the uncertainty from the operation. In the case of MD, the propagation of uncertainty comes equally from civil works, equipment and operation.

(FIGURE 5)

3.2. The contribution of construction to the environmental burden found in the literature

Figure 6 shows the results of the contribution of construction and operation to the global environmental impacts for relevant papers in literature which studied a similar wastewater treatment technology and specified the life span of infrastructure. Overall, the contribution of construction ranges from 1% to 63%. While operation and civil works were considered in all studies presented in Figure 6 (only a few included GHG emissions), equipment was only considered in Vlasopoulos et al. (2006), Machado et al. (2007), Ortiz et al. (2007) and Renou et al. (2008).

(FIGURE 6)

Previous studies reported a share of construction to the overall impacts lower than 5% (Emmerson et al., 1995; Vlasopoulos et al., 2006). We understand that there is probably an underestimation of concrete (we estimated that 3 times more concrete would be needed in a WWTP of the same size compared to Emmerson et al., 1995), and that no databases of construction elements such as Banc BEDEC have been used. The construction inventory for Vlasopoulos et al. (2006) was collected by questionnaire contact to over 160 equipment designers, manufacturers and suppliers, but not based on real information from existing systems and following a detailed budget. No detailed information was provided on how the construction inventory was executed and on the assumptions made.

Renou et al. (2008) concluded that the construction of an activated sludge plant had a contribution of 11% to the CC impact category, close to the 8% reported in this study. However, for the HT impact category they reported a share of construction of 1%, which is much lower than the 18% obtained in this study. The difference might be explained by the fact that they did not include equipment in their inventories.

Some studies reported a share of construction to the overall impacts between 20 and 30% (Machado et al., 2007; Ortiz et al., 2007). The difference compared to our study might be explained by the shorter life span they applied and because of the economy of scale. In addition, the inclusion of N_2O and CH_4 emissions in the operation might have a large influence downgrade the contribution of construction to the overall impacts.

Using the inventory values reported in Foley et al. (2010) (for their scenario 4Bii) and running ReCiPe (H) 1.13 we obtained a contribution for all categories lower than 5% for the construction, except for MD where the contribution of construction was of 18%. From the interpretation of that inventory (it is not explained in detail) we understand that in Foley et al. (2010) they considered materials to build mainly the secondary treatment, but did not include in detail all possible stages (pumping, pretreatment, primary treatment and sludge line). Whereas in Foley et al. (2010) they applied a factor of 77 kg of steel per m^3 of concrete in this study a factor of 90 kg of steel per m^3 was used. That increases the amount of metals, and hence has an effect specially for HT and MD. In addition, whereas in Foley et al. (2010) they accounted for the production of two materials (steel and copper) and the mass for 3 type of equipment (pumps, motors and blowers), we included 30 additional materials and 1240 devices (Table S-2a).

Risch et al. (2015) reports a contribution of 20% for CC, higher than our study (around 8%), a similar one for HT (18%) and a lower contribution for OD, FE, but specially for MD and FD, even though Risch et al. (2015) use a life span of 30 years. The exhaustive inventory for the equipment and civil works phases in our study can be the explanation for these significant differences.

Ecoinvent provides some inventories for construction and operation for 30 years lifespan of 5 different WWTPs. After recalculating the results for 20 years life span for the 5 WWTPs, the average of the construction and operation impacts shows a contribution of the construction for CC (32%) and OD (29 %), which are values higher than our results (8% and 10% respectively). Similar results are obtained for ME, HT and FD, with a contribution of the construction of 0%, 28% and 24% of each one. Finally, for FE the contribution is very similar to our study (around 8%) while for MD the contribution is lower (45% against 65% obtained in our study). Apparently there is a disagreement between the results reported in Ecoinvent and other studies. That disagreement might come from an overestimation of the amount of concrete. Whereas in Ecoinvent a factor of 6268 kg/m^3 is applied, in this study we obtained a factor of 927 kg/m^3. The latter, is within the order of magnitude of other studies, such as 579 kg/m^3 in Foley et al. (2010) or 428 kg/m^3 in Emmerson et al. (1995).

3.3. Identification of key resources/processes that contribute the most to the environmental burden

In this section we identify which are the key resources/processes in the construction and operation of the WWTP of Girona. A summary of the contribution of each of the treatment units to construction, equipment and operation related impacts is provided in Table 3 and illustrated in Figure 7. With regards to civil works, the production of concrete used in the construction of the secondary treatment (mainly the biological reactors) and the sludge line (mainly the anaerobic digester) is the process contributing the most to CC impacts. Then, the production of reinforcing steel (also used to build the biological reactors, the digester and thickeners) is the process that contributes the most to MD (with a contribution on its own of 41% of the total impact, 25% from the biological reactors and 11% from the digester) and to HT (a contribution of 7.6% of the total). Recycling the steel from the reinforced concrete would significantly decrease the MD and HT impacts, although probably at expenses of increase in CC due to the usage of machinery. However, this is not a common practice due to high costs. There is a slight contribution of the production of plastics to HT and MD (lower than 4%). The equipment contributes to 11% of the MD, 3.4% of the HT, and is almost negligible for the CC impacts. Metals consumed during the production of equipment, including pumps and motors, transport and mobile equipment, are contributing the most to MD. When it comes to operation, and looking into CC impact category, then the electricity consumed for pumping & pretreatment and secondary treatment (aeration) correspond to about 20% of the total impact, and the direct GHG emissions emitted from the biological reactor (35% of the total impact, but with large associated uncertainty) are the largest contributors. The electricity produced at the treatment plant through cogeneration corresponds to an avoided impact of about 10%. When it comes to HT and MD, then the chemicals used in primary treatment (i.e. iron chloride) and secondary treatment (i.e. sodium aluminium) also play a significant role, as they contribute to 30% of HT and 20% of MD. Finally, the deposition of solids from the pretreatment to landfill contribute to 17% of the HT. The avoided electricity production has also a positive impact on the HT (16%).

Additionally, Figures S-1 to Figure S-4 illustrate the contribution of civil works, equipment and operation for each operational unit for the other studied impact categories (OD, FE, ME and FD, respectively). In Figures S-2 and S-3 the high influence of the discharge of nitrogen and phosphorus from the WWTP is observed for the eutrophication impact categories.

Previous published works already identified that electricity consumption, chemicals and primary solids are the main contributors to CC, MD and HT (e.g. Hospido et al., 2004, Rodriguez-Garcia et al., 2011) and nutrients discharged to the receiving water bodies (assigned to secondary treatment in this study) are the most important contributors to eutrophication (e.g. Hospido et al., 2008). The fact that concrete and reinforcing steel are also important contributors to the CC and MD impacts has been reported before in Machado et al., (2007). The significant contribution of equipment to MD is an important highlight of this study since has never been reported before, and as estimated in this study can contribute up to 11% of the MD impacts.

(FIGURE 7)

3.4. Influence of inventory simplifications on the environmental impacts

As an exercise of simplification we took the key resources/processes identified in previous sections and calculated the overall coverage of the estimation of the environmental impacts based on factors for materials and energy provided in Table 2. An LCA exercise which would include concrete, reinforcing steel and plastics, together with the operational data (energy, GHG emissions, chemicals and deposition of solids from the pretreatment), would allow to estimate between 90 and 99% of the impact in CC, OD, FE, ME and FD categories. In order to encompass a minimum 90% of the HT and MD impacts, metals consumed during the production of pumps, motors, transport and mobile equipment should be considered in addition to the data mentioned before. From our study, we can conclude that buildings and service units can be omitted from the analysis.

At another simplification level, the inclusion of civil works, equipment and operation of secondary treatment (i.e. biological reactor and settler) and sludge line (i.e. thickeners, anaerobic digester and centrifuges) would result in about 75% coverage of the total impact for the different impact categories in this study.

It is also important to mention that these conclusions are based in a single application of this approach in an activated sludge WWTP of 206,250 PE. For this reason, further work should be conducted to analyze different treatment technologies and different sizes to draw more general recommendations.

4. CONCLUSIONS

An inadequate level of detail for materials and resources inventoried during construction, operation and dismantling processes (e.g. considering or not GHG or metals for the equipment) significantly influences the estimation of the share of construction to the global environmental impacts of WWTPs. With our case study, we demonstrate that for most of the impact categories the contribution of construction to the overall burden is higher than 5% and especially for metal depletion the impact of civil works plus equipment reaches 63%. When comparing to the WWTP inventories available in Ecoinvent, the share of construction is about three times smaller for climate change but twice higher for metal depletion. Although the equipment has a smaller impact than civil works, it must be considered as well; depending on the category and the number of times it has to be replaced, its impact cannot be neglected, particularly in the HT and MD impact categories. Concrete and reinforcing steel are the materials with the highest contribution to the civil works phase and motors and pumps are also key equipment to consider during life cycle inventories of WWTPs. The factors obtained with the most detailed inventory published so far facilitates the development of robust inventories for WWTPs construction, operation and dismantling.

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TABLES

Table 1: Description of all the unit processes included in each operation unit studied.

Table 2: Inventory for the civil works, equipment and operation of the plant divided by unit.

Table 3: Percentage contribution of civil works (CW), equipment (EQ) and operation (OP) for each operational unit and environmental impact studied.

FIGURES

Figure 1: Procedure followed to obtain the detailed inventory of the WWTP construction. EPD: Environmental Product Declaration.

Figure 2: Scheme of the Girona WWTP with a separation of each analyzed unit and the inputs and outputs considered for the operational analysis.

Figure 3: System boundaries considered in this LCA study.

Figure 4: Contribution of civil works, equipment and operation in each impact category, depending on the life span considered. In each category, the first bar, starting from the left, corresponds to a 10-years life span, the second (middle) bar corresponds to 20 years (base case), and the third (right) corresponds to 30 years.

Figure 5: Results of the uncertainty analysis for all analyzed categories. In the case of CC category there are two different error bars, the higher uncertainty range includes the uncertainty of N_2O emissions factor provided in Foley et al. (2010).

Figure 6: Summary of all studies used for the comparison of construction and operational impacts.* Energy consumption as MJ; ** CML estimates eutrophication as a single impact category; *** CML estimates abiotic depletion as a combination of metal depletion (MD) and fossil depletion (FD). The different levels of detail followed in the construction inventories are depicted by the abbreviations

Figure 7: Cumulative impact from 0% to 100% of the resources consumed in civil works, equipment and operation for CC, HT and MD categories. The contribution of each resource/process from each WWTP unit is shown. Results for other studied impact categories are found in supporting information (Figure S-1 to Figure S-4).

Table 1: Description of all the unit processes included in each operation unit studied.

Operational unit	Elementary processes included
Pumping+pretreatment	Wastewater well reception, pumping station, pretreatment building, part of the connections and part of the unit to dose chemicals
Primary treatment	Primary settlers, units to mix water and chemicals, chamber to measure the flow and part of the connections
Secondary treatment	Biological reactors, secondary settlers, chamber to measure the sludge sent to the sludge line, chamber to measure and pump the sludge sent back to the biological reactor, part of the unit to dose chemicals and part of the connections
Sludge line and deposition	Thickening tanks and buildings for the thickening tanks, chamber to pump the sludge, dewatering building, zone for the dewatered sludge, anaerobic digestion unit and part of connections, final sludge treatment in a composting plant
Others	Chemicals storage, control building, adaptation of the land and sidewalks

Table 2: Inventory for the civil works, equipment and operation of the plant divided by unit.

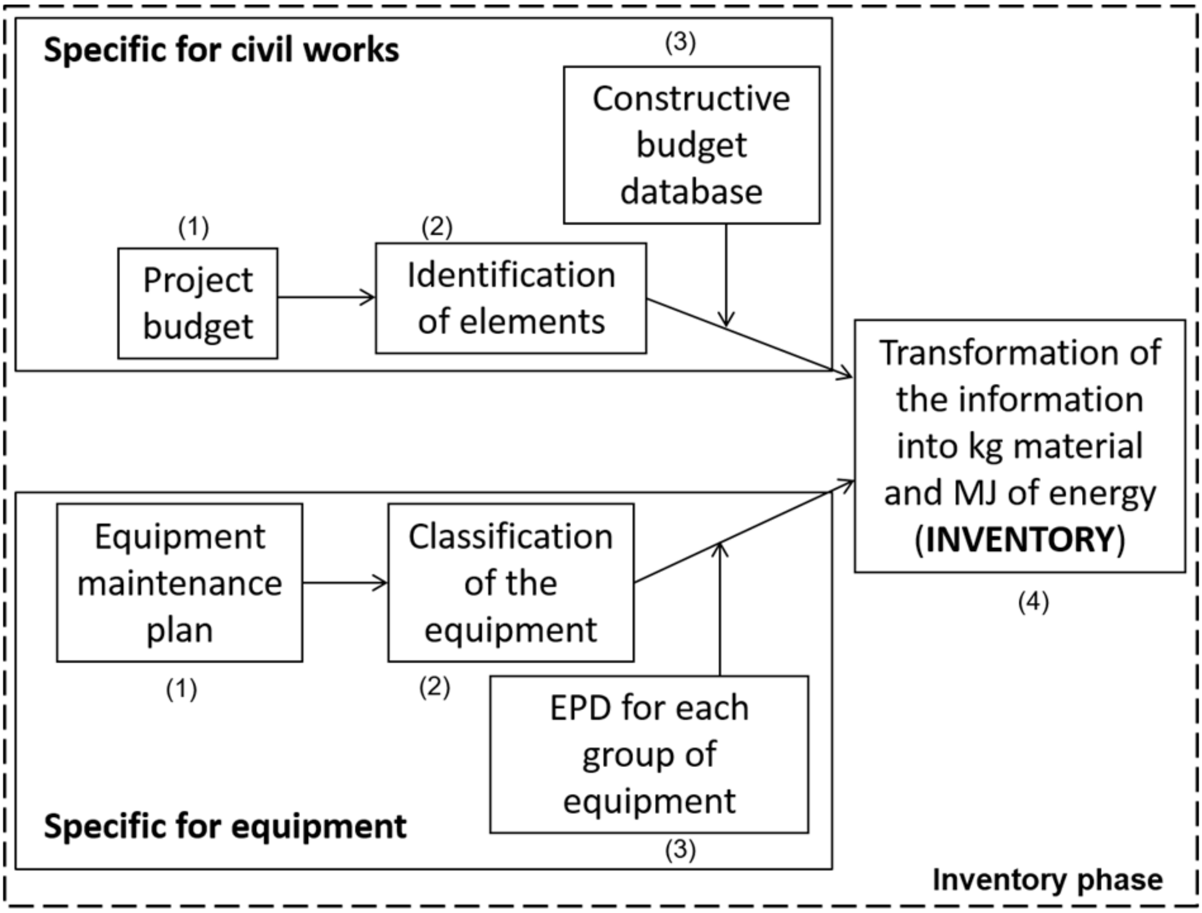
Concept	Unit	Pumping + pretreatment	Primary treatment	Secondary treatment	Sludge line and deposition	Building and services	Full plant
Civil works							
Excavated material	ton·m^{-3}	$1.14\cdot10^{-6}$	$1.00\cdot10^{-5}$	$2.81\cdot10^{-4}$	$2.05\cdot10^{-5}$	0	$3.14\cdot10^{-4}$
Energy consumed	MJ·m^{-3}	$1.07\cdot10^{-3}$	$1.70\cdot10^{-3}$	$2.14\cdot10^{-2}$	$4.83\cdot10^{-3}$	$2.64\cdot10^{-3}$	$2.91\cdot10^{-2}$
Total transport	tkm·m^{-3}	$7.05\cdot10^{-4}$	$8.34\cdot10^{-4}$	$8.89\cdot10^{-3}$	$5.33\cdot10^{-3}$	$3.56\cdot10^{-4}$	$1.61\cdot10^{-2}$
Reinforcing steel	kg·m^{-3}	$4.96\cdot10^{-4}$	$4.23\cdot10^{-4}$	$2.71\cdot10^{-3}$	$1.27\cdot10^{-3}$	$2.05\cdot10^{-5}$	$4.92\cdot10^{-3}$
Metal consumption	kg·m^{-3}	$3.04\cdot10^{-5}$	$3.26\cdot10^{-5}$	$7.52\cdot10^{-5}$	$5.23\cdot10^{-5}$	$1.49\cdot10^{-5}$	$2.05\cdot10^{-4}$
Plastic consumption	kg·m^{-3}	$2.05\cdot10^{-4}$	$2.05\cdot10^{-4}$	$2.12\cdot10^{-5}$	$5.98\cdot10^{-4}$	$2.23\cdot10^{-7}$	$1.22\cdot10^{-3}$
Conglomerates and bricks	kg·m^{-3}	$1.28\cdot10^{-3}$	$5.58\cdot10^{-4}$	$7.20\cdot10^{-2}$	$2.85\cdot10^{-3}$	$6.11\cdot10^{-3}$	$8.28\cdot10^{-2}$
Concrete	kg.m^{-3}	$1.67\cdot10^{-2}$	$1.46\cdot10^{-2}$	$7.17\cdot10^{-3}$	$2.21\cdot10^{-2}$	$1.81\cdot10^{-3}$	$6.24\cdot10^{-2}$
Other materials	kg·m^{-3}	$7.07\cdot10^{-5}$	$1.82\cdot10^{-5}$	$3.79\cdot10^{-5}$	$2.91\cdot10^{-5}$	$9.46\cdot10^{-4}$	$1.10\cdot10^{-3}$
Equipment							
Stainless steel	kg·m^{-3}	$6.03\cdot10^{-5}$	$1.63\cdot10^{-5}$	$2.86\cdot10^{-5}$	$3.26\cdot10^{-5}$	$1.64\cdot10^{-9}$	$1.38\cdot10^{-4}$
Other steel	kg·m^{-3}	$8.72\cdot10^{-6}$	$1.53\cdot10^{-6}$	$1.09\cdot10^{-5}$	$1.66\cdot10^{-5}$	$3.06\cdot10^{-7}$	$3.79\cdot10^{-5}$
Cast iron	kg·m^{-3}	$1.94\cdot10^{-5}$	$3.66\cdot10^{-6}$	$3.49\cdot10^{-5}$	$4.66\cdot10^{-5}$	-	$1.04\cdot10^{-4}$
Aluminium	kg·m^{-3}	$1.19\cdot10^{-6}$	$7.25\cdot10^{-6}$	$2.84\cdot10^{-6}$	$3.49\cdot10^{-6}$	-	$8.22\cdot10^{-6}$
Copper	kg·m^{-3}	$8.29\cdot10^{-7}$	$1.37\cdot10^{-7}$	$1.53\cdot10^{-6}$	$3.89\cdot10^{-6}$	-	$6.40\cdot10^{-6}$
Other metals	kg·m^{-3}	$6.18\cdot10^{-7}$	$1.24\cdot10^{-6}$	$7.27\cdot10^{-7}$	$1.53\cdot10^{-6}$	-	$4.11\cdot10^{-6}$
Polypropylene	kg·m^{-3}	$1.46\cdot10^{-7}$	$3.49\cdot10^{-9}$	$5.90\cdot10^{-6}$	$3.59\cdot10^{-8}$	$2.86\cdot10^{-8}$	$6.10\cdot10^{-6}$
Glass fibre reinforced plastic	kg·m^{-3}	$2.25\cdot10^{-6}$	$1.41\cdot10^{-6}$	$1.42\cdot10^{-6}$	$2.12\cdot10^{-6}$	-	$7.20\cdot10^{-6}$
Polyethylene	kg·m^{-3}	$4.26\cdot10^{-7}$	$9.24\cdot10^{-9}$	$4.78\cdot10^{-7}$	$4.66\cdot10^{-7}$	-	$1.38\cdot10^{-6}$
PVC	kg·m^{-3}	$2.67\cdot10^{-8}$	$1.37\cdot10^{-7}$	$5.21\cdot10^{-8}$	$2.59\cdot10^{-7}$	-	$4.73\cdot10^{-7}$
Polystyrene	kg·m^{-3}	-	$1.15\cdot10^{-6}$	-	-	-	$1.15\cdot10^{-6}$
Other plastics	kg·m^{-3}	$1.39\cdot10^{-7}$	$1.27\cdot10^{-7}$	$2.32\cdot10^{-7}$	$1.17\cdot10^{-7}$	$8.47\cdot10^{-10}$	$6.15\cdot10^{-7}$
Sealing compounds	kg·m^{-3}	$4.56\cdot10^{-7}$	$6.00\cdot10^{-7}$	$3.24\cdot10^{-6}$	$2.49\cdot10^{-6}$	-	$6.77\cdot10^{-6}$
Energy	kwh·m^{-3}	$3.99\cdot10^{-5}$	$2.91\cdot10^{-6}$	$1.06\cdot10^{-4}$	$4.66\cdot10^{-5}$	-	$1.95\cdot10^{-4}$
Other materials	kg·m^{-3}	$7.45\cdot10^{-7}$	$5.55\cdot10^{-7}$	$1.22\cdot10^{-6}$	$9.17\cdot10^{-7}$	$3.04\cdot10^{-7}$	$3.74\cdot10^{-6}$

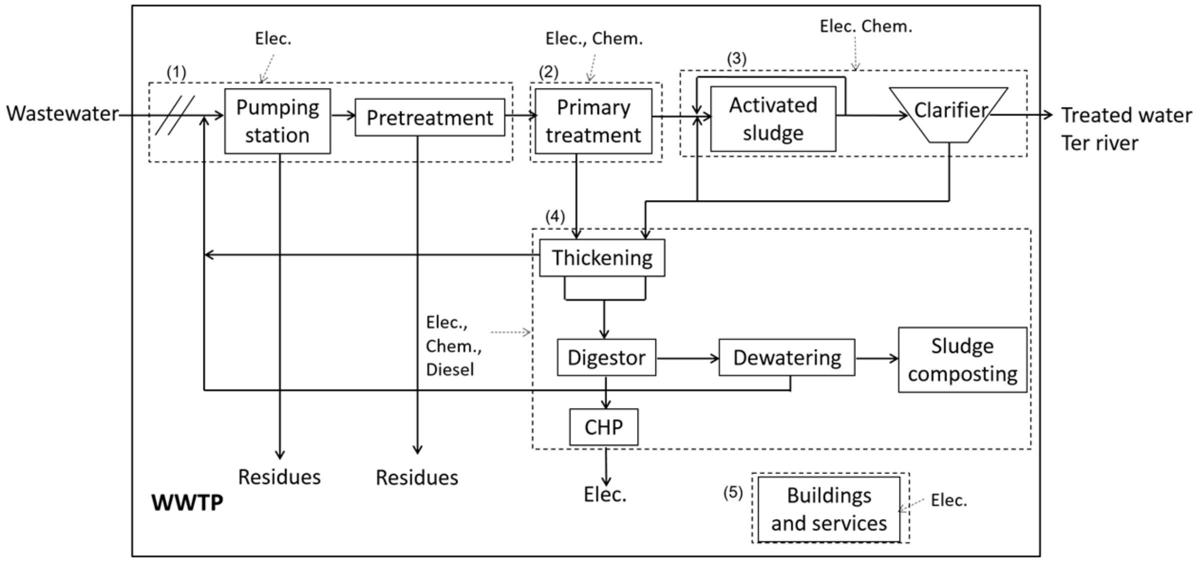
Transport	$tkm \cdot m^{-3}$	$1.44 \cdot 10^{-5}$	$4.28 \cdot 10^{-6}$	$1.44 \cdot 10^{-5}$	$1.68 \cdot 10^{-5}$	$9.84 \cdot 10^{-8}$	$5.01 \cdot 10^{-5}$
Operation							
Electricity consumption	$kwh \cdot m^{-3}$	$7.19 \cdot 10^{-2}$	$1.75 \cdot 10^{-4}$	$2.06 \cdot 10^{-1}$	$5.03 \cdot 10^{-2}$	$2.12 \cdot 10^{-2}$	$3.50 \cdot 10^{-1}$
Electricity production	$kwh \cdot m^{-3}$	-	-	-	$1.31 \cdot 10^{-2}$	-	$1.31 \cdot 10^{-2}$
Iron chloride	$kg \cdot m^{-3}$	-	$1.29 \cdot 10^{-2}$	-	-	-	$1.29 \cdot 10^{-2}$
Sodium aluminate	$kg \cdot m^{-3}$	-	-	$4.27 \cdot 10^{-2}$	-	-	$4.27 \cdot 10^{-2}$
Antifoaming	$kg \cdot m^{-3}$	-	-	$4.74 \cdot 10^{-5}$	$2.49 \cdot 10^{-4}$	-	$2.96 \cdot 10^{-4}$
Polyelectrolyte	$kg \cdot m^{-3}$	-	-	-	$1.24 \cdot 10^{-3}$	-	$1.24 \cdot 10^{-3}$
Antioxidant	$l \cdot m^{-3}$	-	-	-	$2.11 \cdot 10^{-6}$	-	$2.11 \cdot 10^{-6}$
Diesel	$l \cdot m^{-3}$	-	-	-	$2.73 \cdot 10^{-3}$	-	$2.73 \cdot 10^{-3}$
Transport	$tkm \cdot m^{-3}$	$1.16 \cdot 10^{-3}$	$3.70 \cdot 10^{-3}$	$1.35 \cdot 10^{-2}$	$1.58 \cdot 10^{-2}$		$3.42 \cdot 10^{-2}$
Direct GHG emissions	$kg\ CO_{2\ eq} \cdot m^{-3}$	-	-	$2.17 \cdot 10^{-1}$	$4.51 \cdot 10^{-2}$	-	$2.62 \cdot 10^{-1}$
Residues	$kg \cdot m^{-3}$	$3.74 \cdot 10^{-2}$	-	-	-	-	$3.74 \cdot 10^{-2}$
Sludge to composting	$kg \cdot m^{-3}$	-	-	-	$7.88 \cdot 10^{-1}$	-	$7.88 \cdot 10^{-1}$
COD emission	$kg \cdot m^{-3}$	-	-	$1.84 \cdot 10^{-2}$	-	-	$1.84 \cdot 10^{-2}$
NO^{3-} emission	$kg \cdot m^{-3}$	-	-	$1.76 \cdot 10^{-2}$	-	-	$1.76 \cdot 10^{-2}$
PO_4^{3-} emission	$kg \cdot m^{-3}$	-	-	$3.32 \cdot 10^{-4}$	-	-	$3.32 \cdot 10^{-4}$

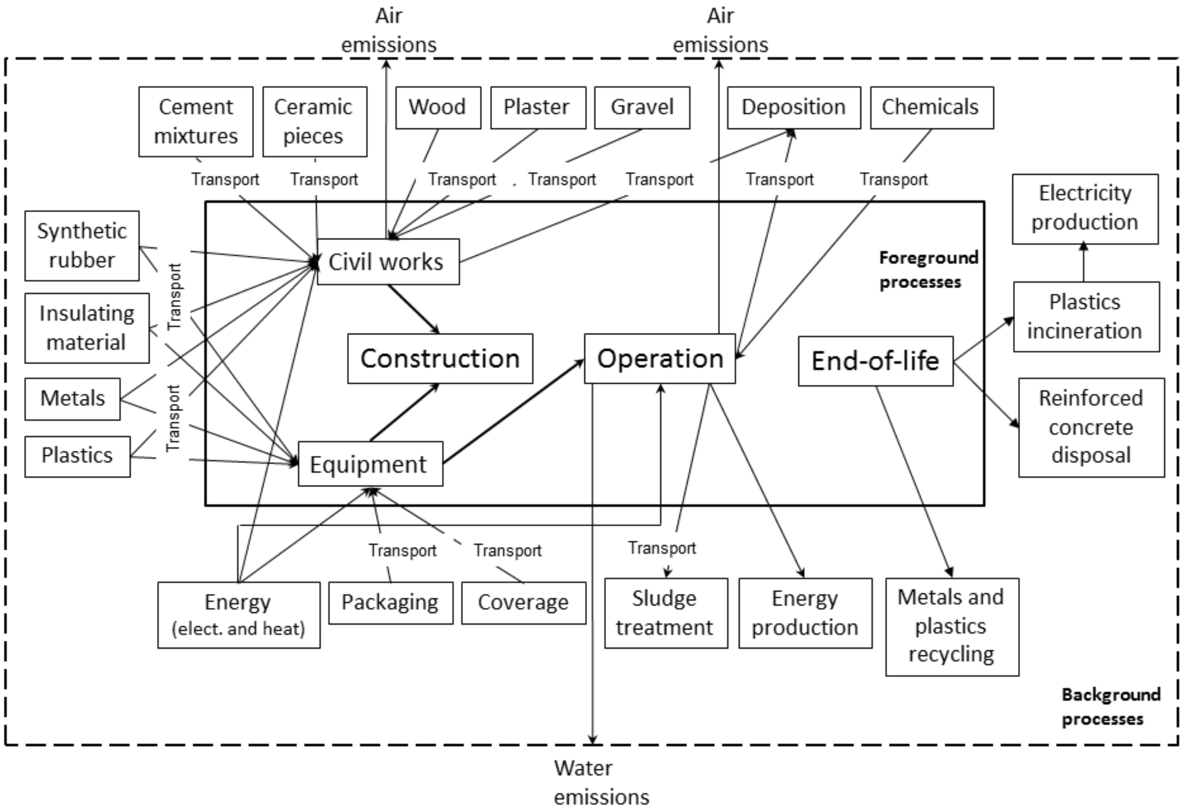
Table 3: Percentage contribution of civil works (CW), equipment (EQ) and operation (OP) for each operational unit and environmental impact studied.

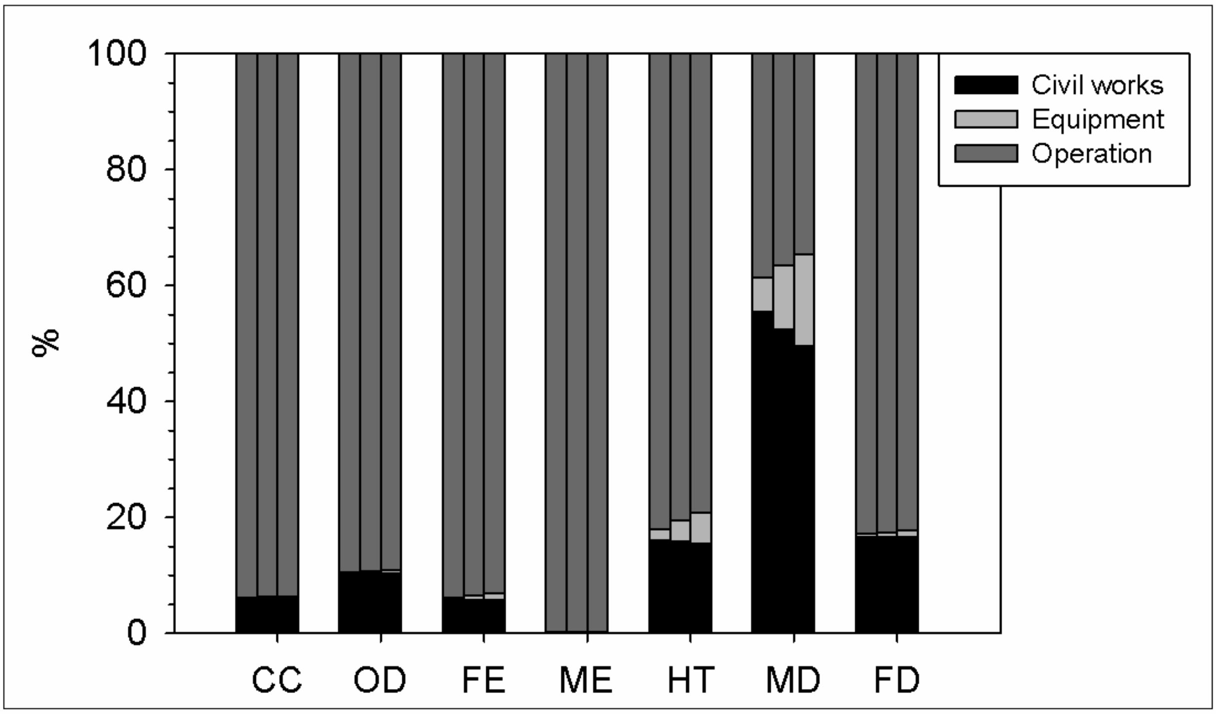
	Pumping + pretreatment			Primary treatment			Secondary treatment			Sludge line			Buildings and services			Total plant		
	CW	EQ	OP	CW	EQ	OP	CW	EQ	OP	CW	EQ	OP	CW	EQ	OP	CW	EQ	OP
CC	8.01	0.78	91.21	20.32	0.73	78.95	5.32	0.09	94.58	5.33	0.20	94.47	9.71	0.02	90.27	6.09	0.20	93.71
OD	9.69	0.88	89.43	5.09	0.32	94.59	7.84	0.18	91.98	111.60	7.58	-19.18[1]	9.86	0.10	90.04	10.25	0.47	89.28
FE	10.66	2.73	86.62	9.67	1.55	88.79	3.18	0.19	96.63	-104.10	-20.58	224.68[2]	5.74	0.06	94.20	5.75	0.75	93.50
ME	0.86	-0.05	99.19	15.64	0.72	83.64	0.10	0.00	99.90	1.42	-0.44	99.02	11.10	0.03	88.87	0.19	-0.02	99.83
HT	6.67	2.41	90.92	10.17	2.41	87.42	15.07	1.45	83.48	253.52	80.11	-233.64[1]	9.57	0.10	90.33	16.06	3.29	80.65
MD	41.25	30.41	28.34	25.96	7.57	66.47	58.03	4.68	37.29	80.28	15.35	4.38[1]	28.18	0.41	71.41	52.83	10.47	36.69
FD	9.78	1.10	89.12	19.85	0.83	79.31	13.59	0.28	86.13	93.52	3.85	2.62[1]	8.57	0.02	91.41	16.84	0.62	82.53

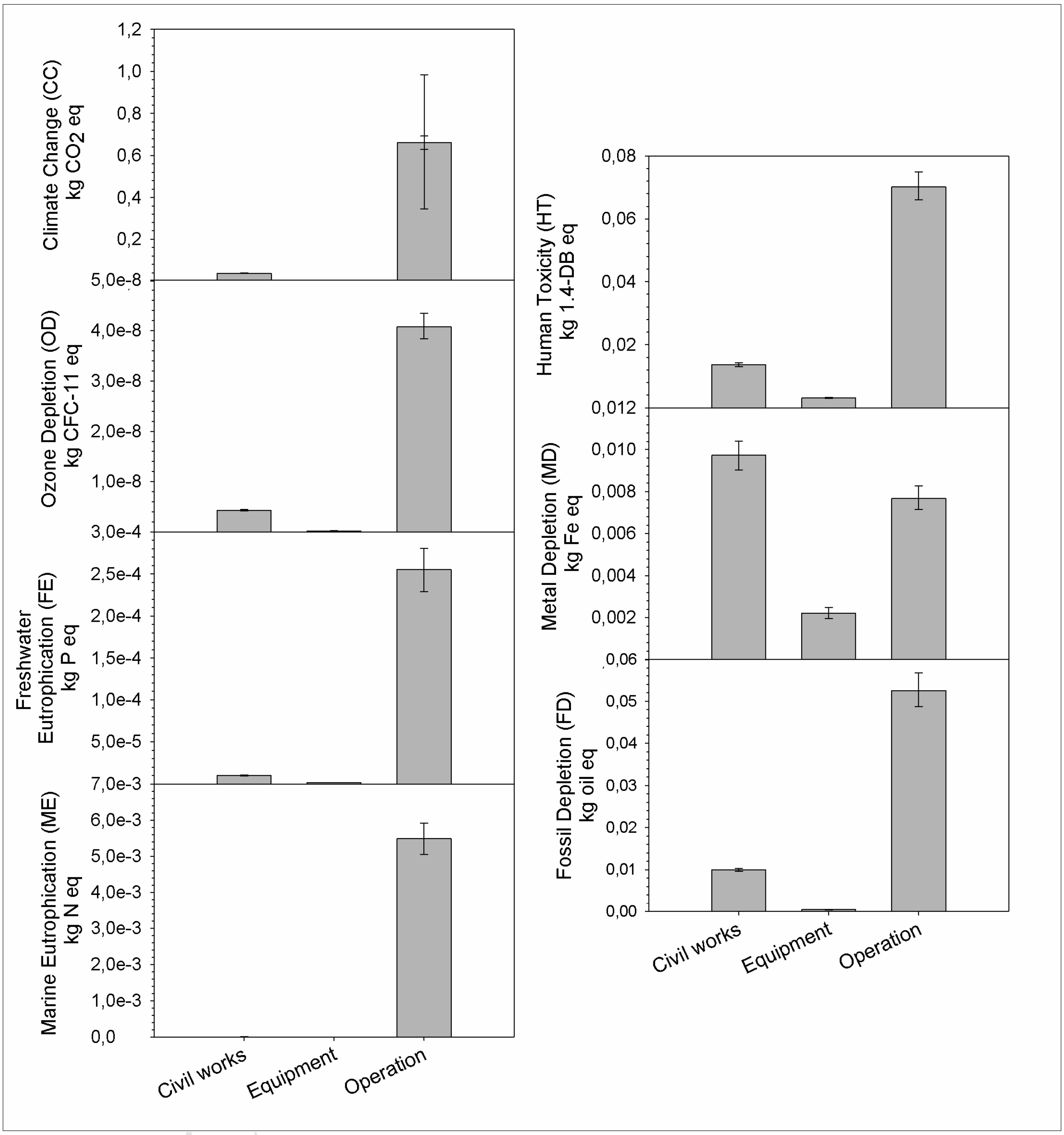
CW (civil works), EQ (equipment), OP (operation), unit of measurement in %. [1] In these cases, due to the electricity produced during the operation the impact generated by the operation is negative. [2] In this case, because the electricity produced is enough to compensate the impact generated by civil works and equipment, for this reason when the contribution of civil works and equipment is compared with the total impact the result is negative.

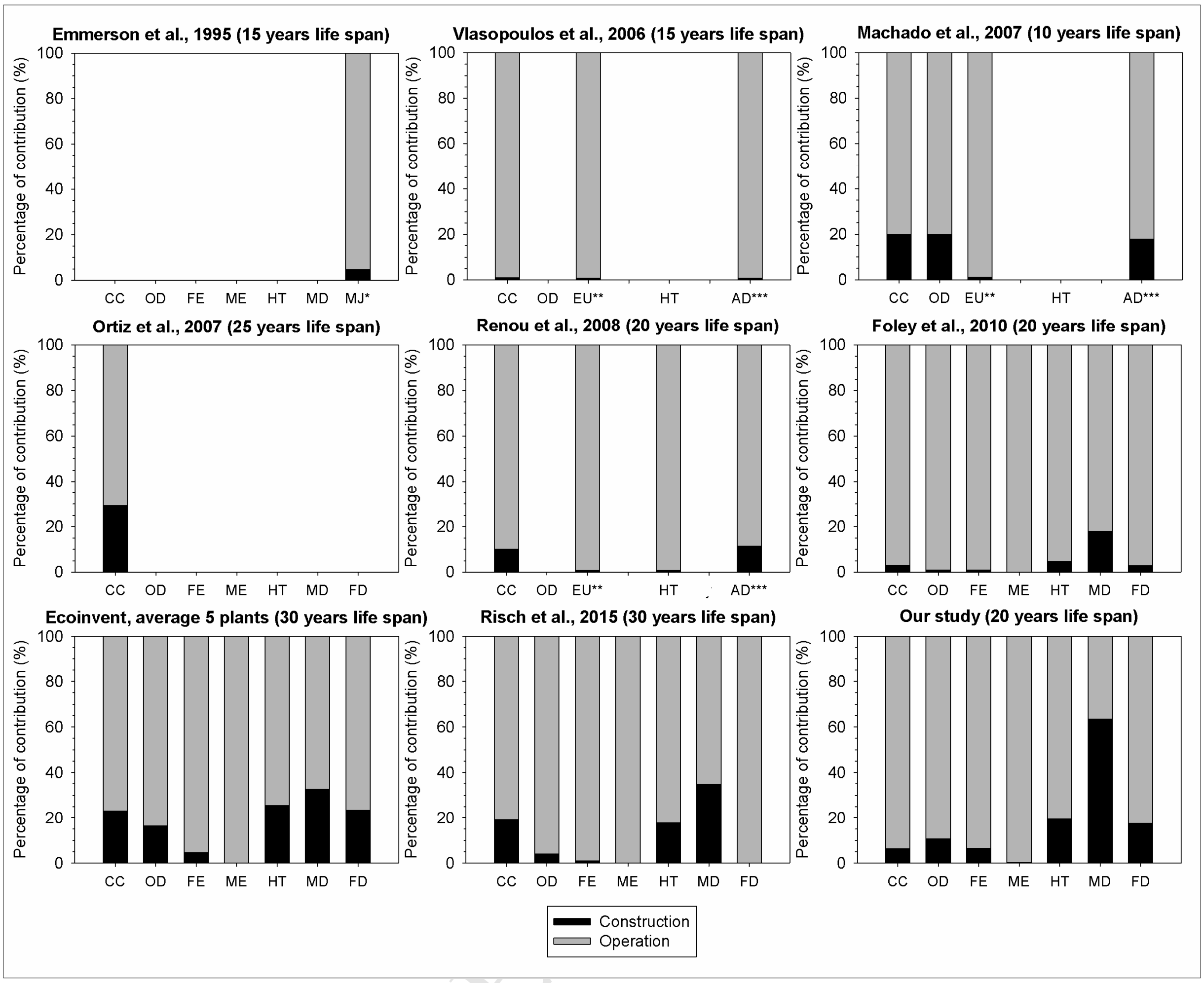

Specific for civil works
(1)
Project budget
(2)
Identification of elements
(3)
Constructive budget database
Transformation of the information into kg material and MJ of energy (INVENTORY)
(4)
Equipment maintenance plan
(1)
Classification of the equipment
(2)
EPD for each group of equipment
(3)
Specific for equipment
Inventory phase

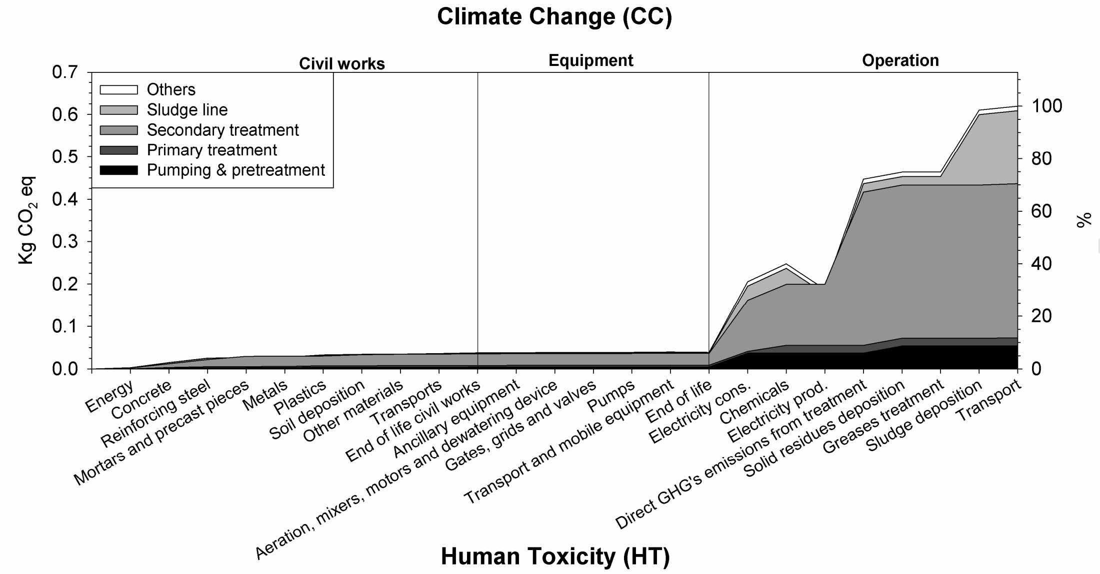

Wastewater
Elec.
(1)
Pumping station
Pretreatment
Elec., Chem.
(2)
Primary treatment
Elec. Chem.
(3)
Activated sludge
Clarifier
Treated water
Ter river
(4)
Thickening
Elec.,
Chem.,
Diesel
Digestor
Dewatering
Sludge composting
CHP
Residues
Residues
Elec.
WWTP
(5)
Buildings and services
Elec.

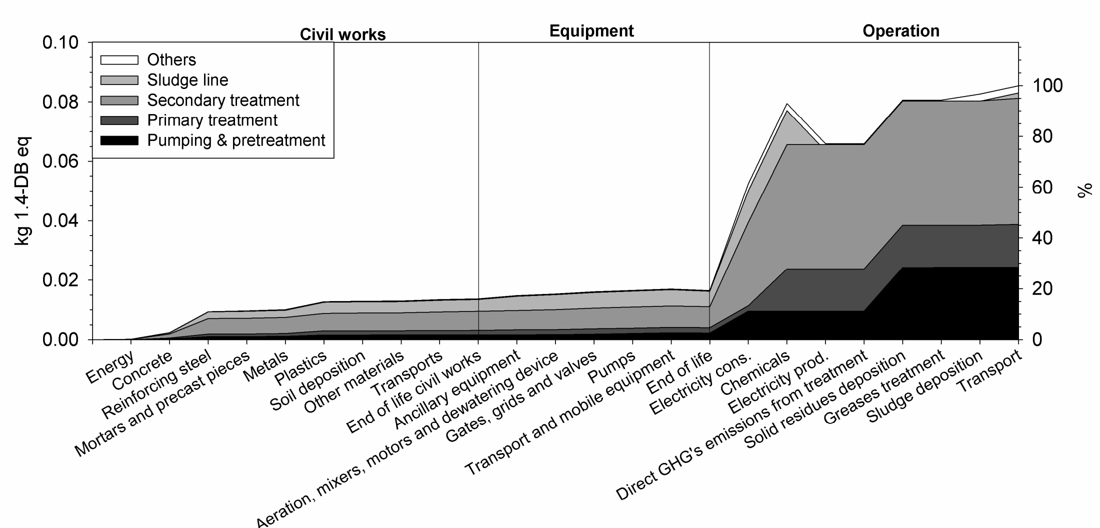

Air emissions
Air emissions
Cement mixtures
Ceramic pieces
Wood
Plaster
Gravel
Deposition
Chemicals
Transport
Transport
Transport
Transport
Transport
Transport
Transport
Synthetic rubber
Insulating material
Metals
Plastics
Transport
Transport
Civil works
Foreground processes
Electricity production
Plastics incineration
Construction
Operation
End-of-life
Reinforced concrete disposal
Equipment
Transport
Transport
Transport
Energy (elect. and heat)
Packaging
Coverage
Sludge treatment
Energy production
Metals and plastics recycling
Background processes
Water emissions

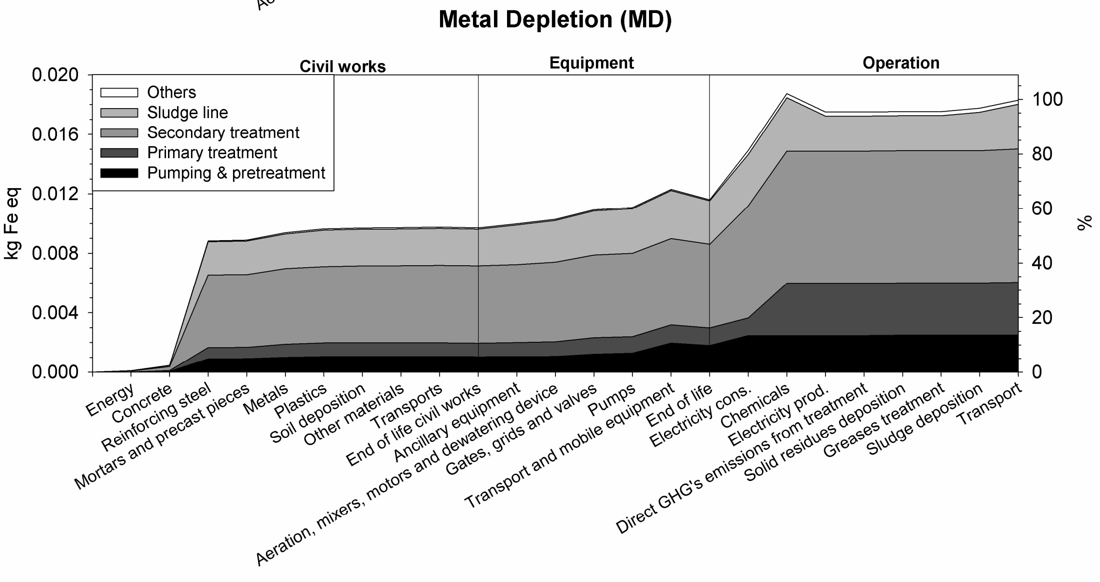

100
80
60
40
20
0
%
CC
OD
FE
ME
HT
MD
FD
Civil works
Equipment
Operation


Climate Change (CC)
kg CO_2 eq
1,2
1,0
0,8
0,6
0,4
0,2
5,0e-8
Ozone Depletion (OD)
kg CFC-11 eq
4,0e-8
3,0e-8
2,0e-8
1,0e-8
3,0e-4
Freshwater
Eutrophication (FE)
kg P eq
2,5e-4
2,0e-4
1,5e-4
1,0e-4
5,0e-5
7,0e-3
Marine Eutrophication (ME)
kg N eq
6,0e-3
5,0e-3
4,0e-3
3,0e-3
2,0e-3
1,0e-3
0,0
Civil works
Equipment
Operation
Human Toxicity (HT)
kg 1.4-DB eq
0,08
0,06
0,04
0,02
0,012
Metal Depletion (MD)
kg Fe eq
0,010
0,008
0,006
0,004
0,002
0,06
Fossil Depletion (FD)
kg oil eq
0,05
0,04
0,03
0,02
0,01
0,00
Civil works
Equipment
Operation


Emmerson et al., 1995 (15 years life span)
Vlasopoulos et al., 2006 (15 years life span)
Machado et al., 2007 (10 years life span)
Ortiz et al., 2007 (25 years life span)
Renou et al., 2008 (20 years life span)
Foley et al., 2010 (20 years life span)
Ecoinvent, average 5 plants (30 years life span)
Risch et al., 2015 (30 years life span)
Our study (20 years life span)
Percentage of contribution (%)
0
20
40
60
80
100
CC
OD
FE
ME
HT
MD
MJ*
EU**
AD***
FD
Construction
Operation


Climate Change (CC)
Civil works
Equipment
Operation
Others
Sludge line
Secondary treatment
Primary treatment
Pumping & pretreatment
Kg CO$_2$ eq
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
%
100
80
60
40
20
0
Energy
Concrete
Reinforcing steel
Mortars and precast pieces
Metals
Plastics
Soil deposition
Other materials
Transports
End of life civil works
Ancillary equipment
Aeration, mixers, motors and dewatering device
Gates, grids and valves
Pumps
Transport and mobile equipment
End of life
Electricity cons.
Chemicals
Electricity prod.
Direct GHG's emissions from treatment
Solid residues deposition
Greases treatment
Sludge deposition
Transport


Human Toxicity (HT)
Civil works
Equipment
Operation
Others
Sludge line
Secondary treatment
Primary treatment
Pumping & pretreatment
kg 1.4-DB eq
0.10
0.08
0.06
0.04
0.02
0.00
%
100
80
60
40
20
0
Energy
Concrete
Reinforcing steel
Mortars and precast pieces
Metals
Plastics
Soil deposition
Other materials
Transports
End of life civil works
Ancillary equipment
Aeration, mixers, motors and dewatering device
Gates, grids and valves
Pumps
Transport and mobile equipment
End of life
Electricity cons.
Chemicals
Electricity prod.
Direct GHG's emissions from treatment
Solid residues deposition
Greases treatment
Sludge deposition
Transport


Metal Depletion (MD)
Civil works
Equipment
Operation
Others
Sludge line
Secondary treatment
Primary treatment
Pumping & pretreatment
kg Fe eq
0.020
0.016
0.012
0.008
0.004
0.000
%
100
80
60
40
20
0
Energy
Concrete
Reinforcing steel
Mortars and precast pieces
Metals
Plastics
Soil deposition
Other materials
Transports
End of life civil works
Ancillary equipment
Aeration, mixers, motors and dewatering device
Gates, grids and valves
Pumps
Transport and mobile equipment
End of life
Electricity cons.
Chemicals
Electricity prod.
Direct GHG's emissions from treatment
Solid residues deposition
Greases treatment
Sludge deposition
Transport

Highlights

- Detailed civil works and equipment inventories for a large WWTP are provided
- Construction share of the environmental impacts is higher than 5%
- For metal depletion, construction can represent >60% of impacts
- Differences are observed when comparing to Ecoinvent inventories