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Reaserch Article

Life Cycle Assessment of Construction of Water Supply Pipelines: A Case Study from Van, Turkey

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Abstract

Pipelines that supply water from water resource to the reservoirs constitute an important part of water supply system construction. In this study, environmental impacts of construction of pipeline component of a water supply system in Van, Turkey are investigated using Life Cycle Assessment (LCA) methodology. Construction of pipelines is executed using conventional open cut system. Life cycle inventory (LCI) of the study is generated using primary data gathered and GaBi Professional database is used for background processes. CML 2001 was the environmental impact assessment method used. According to the results, the main contributors to AP, FAETP, GWP, HTP, MAETP are raw materials used for the production of pipelines which are high density polyethylene granules and carbon black. Most of TETP is generated because of installation of pipelines and sand used for backfilling the pipe trenches is responsible of this. Production and installation of pipelines end up with ADP due to the used materials. Transportation activities executed during the construction of pipelines have environmental impacts in every category considered; however, their contribution is not significant compared to the other activities conducted.

Keywords: Water Supply, Pipeline, Construction, Life Cycle Assessment, Environmental Impact.

Introduction

As stated by the United Nations Educational Scientific and Cultural Organization (UNESCO), water is certainly one of the most vital needs humanity. Because water needs are dependent on population and activities, the urban water cycle is a vital flow in urban areas (UNESCO, 2012). Water supply systems are important infrastructures due to providing water, which is a vital source for human being. There is always need for construction of water supply systems due to still having places which has no reach of water besides the need of increasing capacities of existing water supply systems due to increasing population and related water demand.

Design of water supply systems are designed according to some general principles, which are very well known and defined in related legislations. These rules provide that the constructed systems supply water in required amount and quality in an economic way. Environmental sustainability also becoming criteria for these systems due to increased awareness of environmental problems such as climate change (Burak et al., 2004; Slagstad & Brattebø, 2014).

Various researchers considering different aspects of the topic and using different methodologies (Burak & Mat, 2019; Negi et al., 2019; Kedirkan, 2019) study environmental sustainability of water supply systems. Life Cycle Assessment (LCA) is one of these methods that gives the opportunity of evaluating a product/process quantatively in terms of environmental impacts through its entire life cycle.

There are LCA studies in the literature that focus on pipeline component of water supply systems / wastewater collection systems similar to this study. Pipe material choice and pipe installation methodology are the main concerns investigated.

Sanjuan-Delmás et al. (2014) compare polyvinyl chloride (PVC), high density polyethylene (HDPE), low density PE, ductile iron (DI) and glass fibre reinforced polyester (GFRP) pipes used in water networks through manufacturing, transportation and installation (MTI) phases. According to their results for 200mm pipe diameter, DI and GFRP pipes have higher environmental impacts for all of the impact categories considered: Abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (ODP), photochemical oxidation potential (PCOP) and cumulative energy demand (CED). Also, they found out that installation phase has the highest contribution compared to pipe production and transportation phases. In Hajibabaei et al. (2018)'s study on drinking water network pipelines, it was determined that DI pipes have the highest environmental impact among PVC, HDPE, DI, fibrocement, and steel pipes for MTI phases. In their study, results are presented for the following environmental impact categories: GWP, ODP, POCP, AP, EP, CED. Authors also included four different trench methods in their scenario analysis and concluded that fibrocement type I trench has the highest impact compared to others due to having a concrete bed, which is also a finding of Petit-Boix et al. (2014). Du et al. (2012) also compared waste and wastewater pipeline materials (PVC, DI, cast iron, HDPE, concrete, and reinforced concrete) in terms of GWP and they included use phase in their system boundary differently than the previously mentioned studies. According to their results, DI was the worst material for pipe diameters of ≤61cm while PVC is the worst one for pipe diameters of ≥76cm and concrete was the best material in terms of GWP for all of pipe diameters considered. Also, in Vahidi et al. (2016)'s study comparing sewer systems made of composite fiber reinforced polymer (FRP), PVC, HDPE, DI, vitrified clay, and reinforced concrete, again DI was responsible of highest environmental impacts in all impact categories (ODP, GWP, Smog, AP, EP, carcinogenics, non-carcinogenics, respiratory effects, ecotoxicity) except fossil fuel depletion considering MTI phases. Shi et al. (2019) evaluated usage of bamboo winding composite pipe usage in water supply systems instead of PVC pipes. Their result showed that there is a significant amount of decrease in all environmental impact categories (1.1-488.8 times) except eutrophication index as well as in CED (3.4 times). Vinidex Systems and Solutions (2018), prepared environmental production declaration (EPD) document for their various pipe products. According to this document, which is also used in this study in life cycle inventory (LCI), raw materials, their transport and pipe production processes have highest shares in ADP (elements), AP, EP, GWP values varying between ~ %54.03-75, which is followed by installation (~ %24-54) and transportation (~ %0.78-1.3) phases.

Loss et al. (2018) compared open cut and pipe bursting systems, which are pipe-relining methodologies, in terms of environmental impacts using ReCiPe 2008 H/H Europe Midpoint method. Due the lower need of soil excavation, backfilling of the trench and related fuel consumption, pipe-bursting methodology was advantageous for all environmental impact categories. Piratla et al. (2012)'s study also included a different trenchless pipe laying methodology, horizontal directional drilling (HDD), which has lower environmental impact compared to conventional methods.

In this study, environmental impacts of construction of pipeline component of a water supply system project in Van, Turkey is evaluated using LCA methodology. With this study, it is aimed to determine the main parameters that are effective on environmental sustainability of pipelines, elucidate their contribution to the total impact and pointing out environmental hotspots leading to activities to decrease environmental impacts. There is a very limited number (Elginoz et al., 2019) of LCA studies that analyses water treatment plants in Turkey. However, up to our knowledge, this is the first study conducted in Turkey for a water supply line project. Thus, this study will be a good reference for researchers as well as to construction sector and decision makers presenting the impacts of a pipeline construction in Turkey.

Materials and Methods

LCA is a method that provides quantitative information related to environmental impacts of a product/process through its life - from production to disposal-. Besides presenting final environmental performance of product/processes, it also gives the opportunity of evaluating them at the design stage, which might end up with more sustainable solutions.

Implementation of a LCA study is regulated with ISO 14040- Environmental management- Life cycle assessment - Principles and framework. According to this standard, four main stages follow each other to complete the study: Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation. LCA is an iterative methodology thus mentioned stages could be repeated to produce more refined results (Baumann & Tillman, 2004; Andries et al., 2018).

In this study, environmental impacts of construction of pipeline component of a water supply system in Van, Turkey is evaluated using LCA methodology. In the following, detailed information is presented related to conducted study in four main LCA stages applied according to ISO 14040-14044 standards.

Goal and Scope

The aim of this study to determine environmental impacts of pipe laying component of a water supply system constructed in city of Van, Turkey. Constructed water supply system covers 9 water supply lines connecting Edremit, Gevaş, Çiçekli, Gürpinar districts and some neighbour villages (Fig. 1).

Water supply system consists of different units such as pipelines, reservoirs, pumping stations, chlorination buildings, other auxiliary structures, etc. This study focuses on only pipeline component of the mentioned project. Specifications of the pipelines in the project are listed in Table 1.

Functional unit of the study is supplying 1 m3 of water for 35 years to the project area. GaBi software is used for data entry and LCIA calculations.

System boundary of the study is determined using cradle-to-gate approach. Manufacturing, Transportation and Installation stages of the pipelines are included in the study.

Fig. 1. Project location (Google Maps, 2019).

Table 1. Pipeline Characteristics

Pipe Diameter	Pressure Rating	Pipe Length (m)
Ø110	PN10	24595.97
Ø110	PN12.5	3706.27
Ø110	PN16	2655.04
Ø125	PN10	196.04
Ø125	PN16	7147.43
Ø125	PN25	5943.63
Ø140	PN10	114.04
Ø160	PN10	1200.84
Ø160	PN16	1419.01
Ø225	PN10	840.63
Ø225	PN12.5	916.68
Ø250	PN10	167.61
Ø280	PN10	430.72
Ø315	PN10	6782.61
Ø355	PN10	566.88

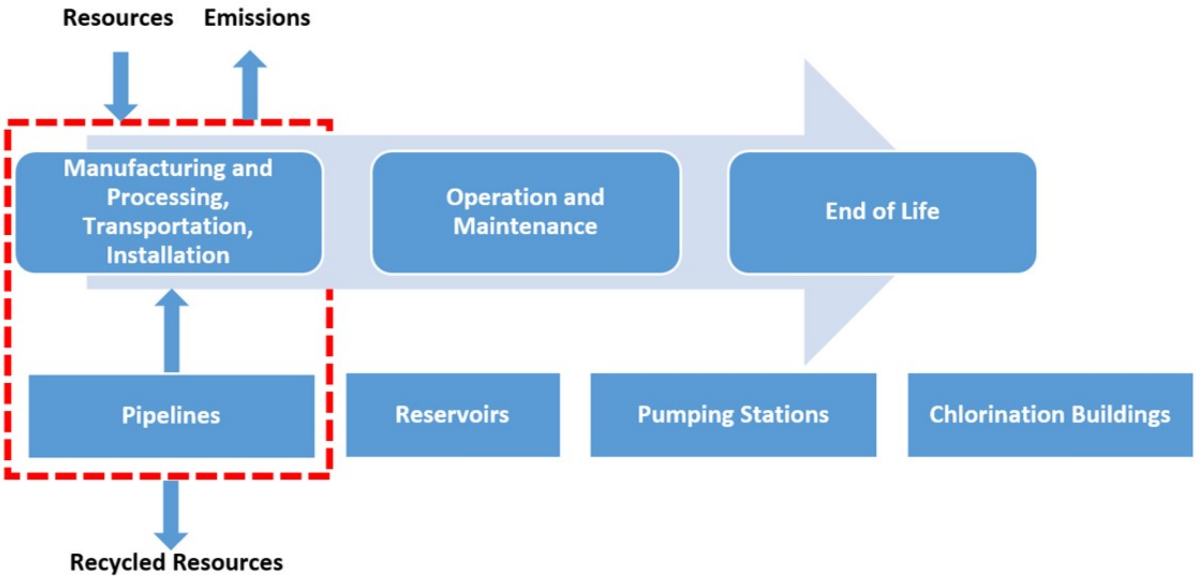

Fig. 2. System boundary of the study.

Certainly, pipelines will require maintenance during the operational phase. However, they do not require serious regular maintenance activities; except flushing of pipelines followed by disinfection by the aim of removing impurities. In case of instantaneous breakdowns, some repair activities are needed those are replacement of parts like gaskets, valves, joints which might require excavation, cement solution, welding/plastic welding depending on the situation (Pradhikaran, 2012). Because, the contribution of maintenance activities are clearly negligible and breakdowns are exceptional cases, operation and maintenance phase is excluded from the system boundaries of this study. End-of-Life stage of the project is also excluded due to being unclear. System boundary of the study is presented in Fig. 2. Project lifetime is planned as 35 years.

Life Cycle Inventory (LCI)

LCI of the study consists of primary data collected from the construction company of the project. While no primary data exists, data from scientific literature catalogues and internet sites are used as secondary data. Besides, some assumptions are made when needed. In addition, GaBi Professional Database was the main source of information to convert collected material amounts into environmental impacts providing background production process information. In Table 2, GaBi Professional Database entries used in the study are listed. The criteria for choosing these was using the process, which is the closest one to the real material/process as well as to Turkey in terms of distance. As a result, generally the database items, which are European average values, are the ones used in this study.

Pipe Manufacturing

Data related to the pipe manufacturing is collected using a previously published Environmental Product Declaration (EPD) for HDPE water supply pipes (Vinidex Systems and Solutions, 2018). Mentioned EPD includes a table of material content of the pipes. According to this resource, HDPE pipes consist of 96-98% of polyethylene, 2-3% of carbon black and <1% of non-hazardous proprietary additives. Due to very low percentage of non-hazardous proprietary additives and uncertainty of their exact content, they are excluded. Using these values, required amount of raw materials were calculated depending on the unit weight of the pipes according to their diameters and unit weights. During the calculations, the density of HDPE was taken as 960 kg/m3.

Transportation

Transportation is used for providing resources for pipe production, carrying produced pipes to the construction area and taking the produced wastes to the disposal areas. Transportation distances of this study is not provided by the company. Thus, standard transport distances, which is proposed by Ecoinvent database guideline are used (Frischknecht et al., 2007). This is a common applied method in LCA studies in case of transport distances are not known. In Table 3, standard transport distances used in the study are presented.

Pipe Installation

Pipe installation covers trench excavation for pipe laying, trench backfilling and soil compaction as the processes related to field preparation as well as pipe cutting. In following, details of inventory data of these processes are presented.

Table 2. GaBi Professional Database background processes used in the study

Process	GaBi Professional Database Processes
Diesel in construction machine	EU-28: Diesel mix at filling station
Transport	EU-28: Transport, truck-trailer (40 t)
	RER: Lorry (22t) incl. fuel ELCD
	EU-28: Transport, truck-trailer (40 t total cap., 24.7t payload) (A4)
Electricity	EU-28: Electricity grid mix (production mix)
Landfill	GLO: EOL: Waste to disposal (e.g. landfill, energy recovery).
Plastic extrusion	GLO: Plastic extrusion profile (unspecific)
Polyethylene granulate	RER: Polyethylene high density granulate (PE-HD) ELCD/PlasticsEurope
Lubricants	EU-28: Lubricants at refinery
Thermal energy	EU-28: Thermal energy from natural gas
Compressed air	GLO: Compressed air 7 bar (high power consumption)
Carbon black	DE: Carbon black (furnace black; general purpose)
Sand	EU-28: Sand 0/2

Table 3. Standard transport distances (Frischknecht et al., 2007)

Material / Target Place For Transportation	Transport Distance (km)
Aggregate / Sand	50
Cement	100
Plastics	100
Chemicals	100
Waste incineration plant	10
Landfill area	10

Trench Excavation

Conventional trench excavation methodology is used during the project. Amount of excavation amount to prepare soil for pipe laying is obtained from the construction company as primary data. For the parts that no related data is provided, excavation amounts are calculated using the simple formula below that was generated by using the technical drawings prepared for the project (Fig. 3):

Excavation amount for 1 m of pipe = $\left((2 \times 0.2) + D\right) \times (0.2 + D + 1) \times 1$

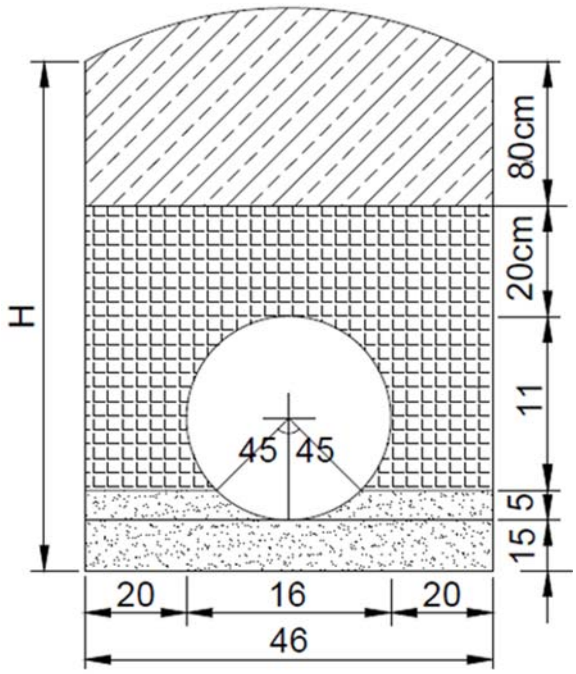

Fig. 3. An example pipeline trench cross-section

Table 4. Calculated amounts for 1-m pipe laying

Pipe Diameter (mm) and Pressure Class (PN)	Excavation Amount (m^3)	Soil Compaction Area (m^2)	Backfilling Amount (m^3)	Required Filling Material Amount (m^3)	Amount of Excess Soil to Landfill (m^3)
Φ110, PN10	0.64	0.51	0.66	0.31	0.35
Φ110, PN12.5	0.64	0.51	0.66	0.31	0.35
Φ110, PN16	0.64	0.51	0.66	0.31	0.35
Φ125, PN10	0.67	0.53	0.68	0.33	0.35
Φ125, PN16	0.67	0.53	0.68	0.33	0.35
Φ125, PN25	0.67	0.53	0.68	0.33	0.35
Φ140, PN10	0.70	0.54	0.71	0.35	0.36
Φ160, PN10	0.73	0.56	0.74	0.38	0.36
Φ160, PN16	0.73	0.56	0.74	0.38	0.36
Φ 225, PN10	0.86	0.63	0.85	0.49	0.36
Φ225, PN12,5	0.86	0.63	0.85	0.49	0.36
Φ250, PN10	0.91	0.65	0.89	0.54	0.36
Φ280, PN10	0.97	0.68	0.94	0.59	0.35
Φ315, PN10	1.05	0.72	1.01	0.66	0.35
Φ355, PN10	1.14	0.76	1.08	0.74	0.34

In the formula, D is the pipe diameter; 0.2 m is the trench width at two sides of the pipe, 0.2 m and 1 m are the material thickness at the bottom and top of the pipe laid, respectively (Fig. 3). In Table 4, all of the excavation amounts calculated are presented.

The excavation machine used in the project is unknown, so calculations have been formed taking into account the generic equipment features commonly used in construction projects. Unit diesel consumption amount of the chosen equipment at dense working hours is 23-30.5 liters and the maximum of this range is chosen as the base for calculation of total diesel usage during excavation processes of the project. Density of diesel is assumed as 832 kg/m3 for calculations. The amount of excavation executed in one hour is calculated using a generic formula as below (Equation 1.) (https://sciencing.com/how-7995132-calculate-excavator-productivity.html):

$$Q = \frac{60 \times q \times z \times n \times K_f}{k_l} \qquad \text{(Eq.1)}$$

Here, Q is the excavator efficiency, q is the volume of one bucket (38.85 ft3), z is the bucket number (z =1), Kf is the filling factor that is taken as 1, kl is the soil loosening factor taken as 1.4 and n is rotor bucket speed (10.2 rpm); however due to possible delays this value assumed as 5 rpm.

Because none of the excavated material was used for backfilling (Fig. 3), excess amount of excavated material is assumed to end in landfill. Thus, transport of this material is also included.

Trench Backfilling

After laying of pipes, excavated trenches are backfilled with provided sand and some amount of excavated soil is also used as the top layer (Fig 3). Using the technical drawings of the pipe cross-sections, amount of backfilling material is calculated using the generated formula below (Equation 2.):

$$\left[\left[\left((2 \times 0.2) + D\right) \times (0.15 + 0.05 + 0.11 + 0.2)\right] - \left(\frac{\pi D^2}{4}\right)\right] \times 1 \quad \text{(Eq.2)}$$

As it can be seen from the figure and the formula, amount of backfilled soil is calculated as the difference between the mounts of excavated soil and filled new sand. When it is needed during data entrance to GaBi software, the density of sand and soil are assumed as 1700 kg/m3 and 1800 kg/m3, respectively.

It is assumed that backfilling was done by using a Caterpillar D7G dozer which can handle 229.37 m3 material in one hour according to the formula below (Equation 3.) (https://sciencing.com/how-7995132-calculate-excavator-productivity.html):

$$\text{Total duration} = \frac{Q}{P \times N} \quad \text{(Eq.3)}$$

Here, P is the efficiency of the equipment, Q is the total amount of material backfilled and N is the number of equipments used. The amount of diesel consumption for the equipment per one hour of working is assumed as 20 liters (Kecojevic & Komljenovic, 2011).

Soil Compaction

Soil is compacted as the final process of pipe laying after trench excavation and backfilling processes. Because used equipment is known during this process, a suitable soil compacting machine is used and related equipment catalogue is used to obtain required technical information for the inventory (https://www.northerntool.com/shop/tools/product_200659933_200659933). The machine compacts 650 m2 soil in one hour and consumes 0.7695 kg of diesel for this. The amount of soil compaction for 1-m of pipe laid is calculated similarly to the trench excavation process using Equation 4.

$$D + (2 \times 0.2) \quad \text{(Eq. 4)}$$

Pipe Cutting

During the pipe installation, pipes are required to be cut in the field. Due to uncertainty of the equipment, a suitable one is chosen to be included in the calculations (https://www.csunitec.com). Considered cutting machine has a power of 2 kWh and it is assumed that pipe cutting machine is used for 1 hour per 1 km length of pipe laid.

Water Supply

Population and water demand projections were executed in the context of the project design. Calculated water demand for time intervals are as follows: 2493.05 L/s for 2010, 2520.93 L/s for 2015, 2616.04 L/s for 2020, 2754.27 L/s for 2025, 2925.82 L/s for 2030, 3109.67 L/s for 2035, 3314.28 L/s for 2040 and 3571 L/s for 2045. Using these values, total supplied water amount for the whole project lifetime is calculated as below (Equation 5.)

$$(2493.05 + 2520.93 + 2616.04 + 2754.27 + 2925.82 + 3109.67 + 3314.28 + 3571) \times 86400 \times 365 \times 5 \times 10^{-3} = 3674741861\, m^3 \quad \text{(Eq.5)}$$

This value is used for giving the results per functional unit of the study.

Impact Assessment

Impact assessment calculations are made by using GaBi software. This program gives the opportunity of producing results in many LCIA methods. CML 2001, January 2016 version is the method chosen for this study due to being the most common method used in pipeline LCA studies. Selected impact categories are abiotic depletion potential (ADP, elements), acidification potential (AP), eutrophication potential (EP), fresh water aquatic ecotoxicity potential (FAETP), global warming potential (GWP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP) and terrestrial ecotoxicity potential (TETP).

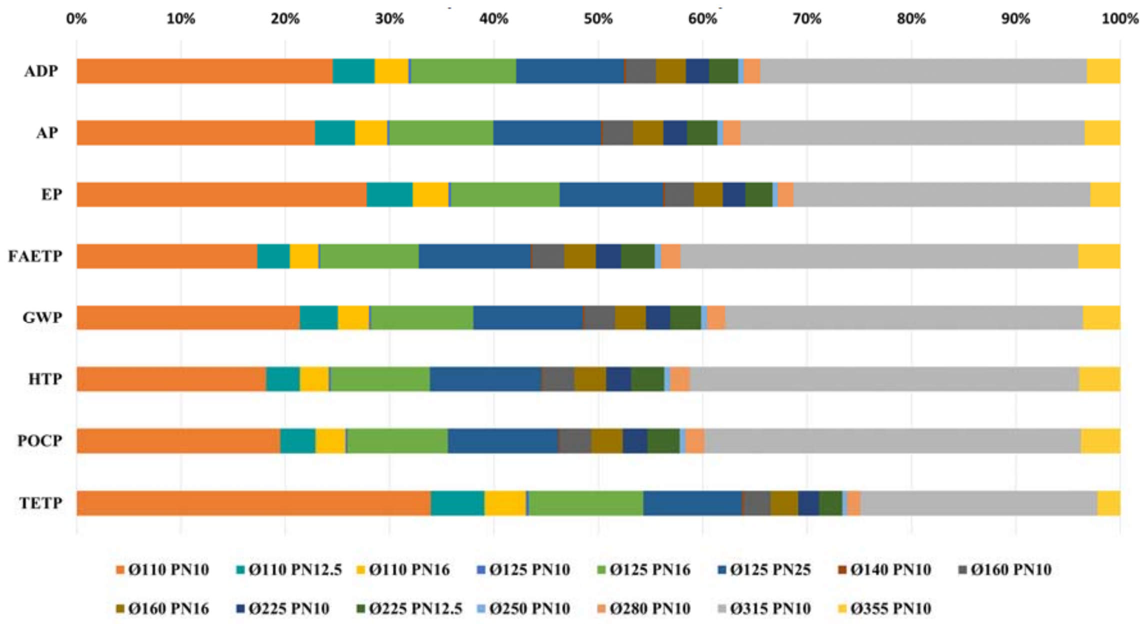

Fig. 4. Contribution analysis per pipelines

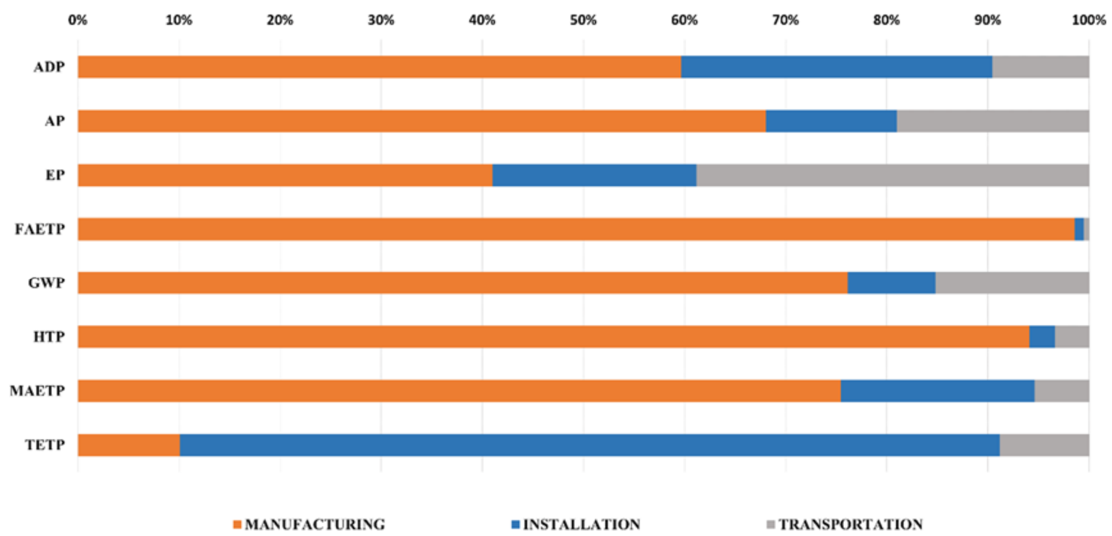

Fig. 5. Contribution analysis for MTI phases.

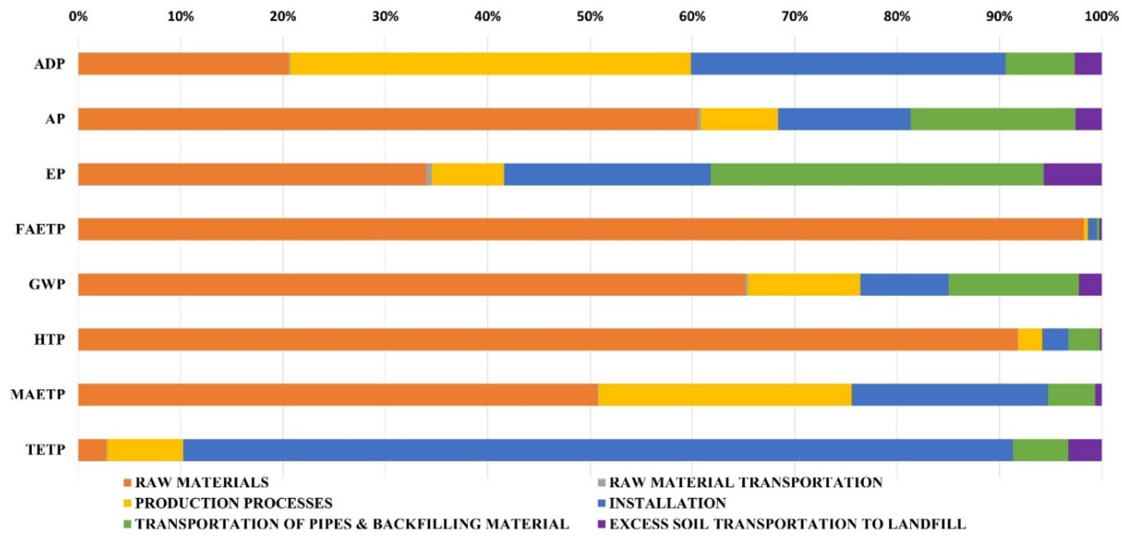

Fig. 6. Detailed contribution analysis for MTI phases including sub-processes

Results

Total environmental impact results of the all of the pipelines in the project are presented in Table 5. In Figure 4, total environmental impacts are presented in terms of contribution of different pipes. As it can be seen from the figure, highest impacts comes from Ø315 PN10 and Ø110 PN10 that have highest pipe diameter and longest construction length, respectively (Table 1). Ø315 PN10 and Ø125 PN10 have very close lengths, however because of high diameter difference, Ø125 PN10 has lower environmental impact values in each category included. Ø140 PN10 is the pipe with the minimum environmental impact due to being the shortest pipeline constructed.

Table 5. Total environmental burdens in terms of impact categories per functional unit.

Environmental Impact Category	Unit	Total Amount
ADP	kg Sb-Eq	1.91E-11
AP	kg SO_2-Eq	7.05E-03
EP	kg PO_4-Eq	9.18E-07
FAETP	kg DCB-Eq	1.06E-07
GWP	kg CO_2-Eq	1.44E-05
HTP	kg DCB-Eq	2.57E-04
MAETP	kg DCB-Eq	1.24E-02
TETP	kg DCB-Eq	1.26E-02

Contribution of manufacturing, transportation and installation (MTI) phases to the total environmental impacts is analysed with Figure 5. Manufacturing phase is a combination of required raw materials, materials and energy for the production of pipelines. In installation phase, pipe cutting, trench excavation, trench backfilling, soil compaction are included. Transport phase includes transportation of raw materials for pipe production, transportation of produced pipes to the project area, transportation of sand for trench backfilling and transportation of excess soil generated during excavation process. As it can be seen, manufacturing is the main contributor to the most of the impact categories with very high percentages changing between 41 to 98% except TETP. Installation is mostly responsible (81%) of TETP results due to sand supply for backfilling of pipe trenches. Besides, contribution of transportation activities to EP is very close (38.8%) to share of manufacturing (41%) due to NOx emissions of vehicles.

To evaluate the study in terms of literature results, studies conducted for water supply or sewer lines for same material (PE100) and similar pipe diameter values are used. Studies in the literature generally uses the unit pipe length as functional unit. Thus, Ø225 plan in GaBi software is run for 1 m pipe length to have a meaningful and valid comparison process. As it can be seen from Table 6, results calculated for Ø225 is very compatible for GWP, AP and EP values with studies on LCA of pipes with a diameter of Ø200. GWP, AP and EP are chosen for the comparison due to being the common environmental impact categories of all studies considered. There is acceptable difference which might be sourced from different construction techniques used, different pipe diameter and LCIA methodology used.

Table 6. Comparison with previous studies

Reference	LCIA Methodology	Ø (mm)	GWP (kg CO_2 -Eq)	AP (kg SO_2-Eq)	EP (kg PO_4-Eq)
This study	CML2001	225	2.63E+01	9.24E-02	1.01E-02
Sanjuan-Delmás vd., (2014)	CML 2 baseline 2000	200	3.70E+01	1.77E-01	4.26E-02
Hajibabaei vd., (2018)	CML 2 baseline 2000	200	3.81E+01	1.68E-01	3.22E-02
Vahidi vd., (2016)	TRACI	200	1.65E+02	1.43E+00	2.10E-02

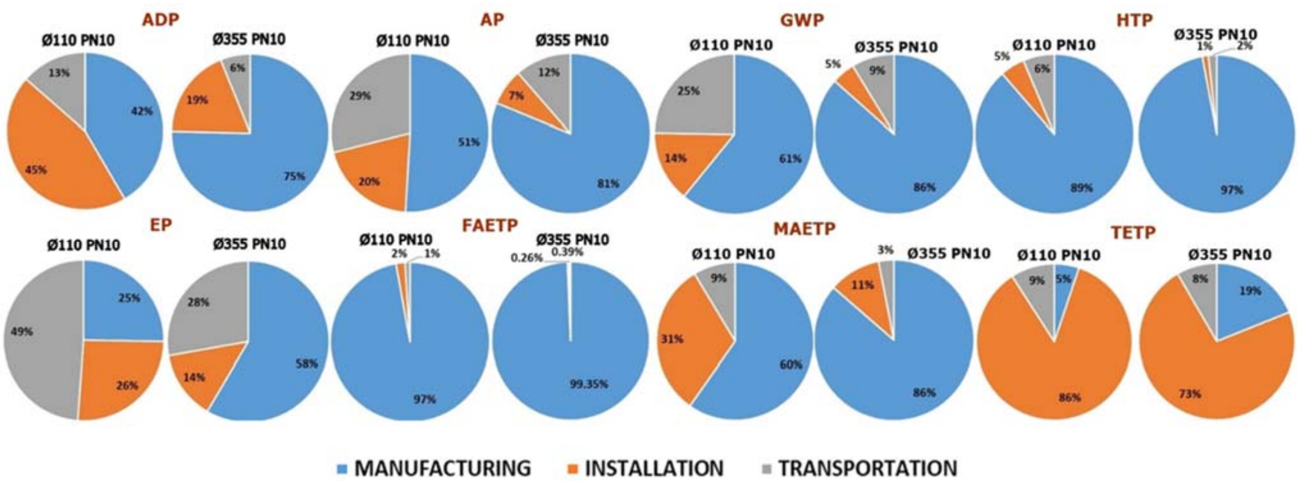

Fig. 7. Contribution analysis of processes in the context of pipe types

For further explaining MTI phases, a more detailed figure which explains the contributing background processes in each phase is presented (Fig. 6). As it can be seen, raw material extraction is the prevailing stressor of the manufacturing processes except ADP and TETP. Contributors to ADP in context of element extraction is used elements by the aim of producing energy (included in production processes), producing pipes (high density polyethylene granules and carbon black production is based on petrochemicals) and providing elements for trench backfilling. Contribution of raw materials is especially high for FAETP (~98%), HTP (~92%), AP (~82%) and MAETP (~51%) due to the production processes of high-density polyethylene granules and carbon black. TETP is mainly sourced from sand extraction (~77%) for backfilling pipe trenches included in the installation processes. Transportation of pipes and backfilling materials and excess soil transportation to landfill significantly contribute to EP results, while they are not important actors of other environmental impact categories considered.

When the results are analysed in the context of pipe diameters, it is observed that for all of the environmental impact categories except TETP, share of manufacturing in total impacts increases as pipe diameter gets bigger which is compatible with the previous studies in the literature (Sanjuan-delmás et al., 2014). Installation phase is the main responsible of terrestrial toxicity and its contribution decreases with increasing pipe diameters. As the pipe diameter increases, required sand to backfill excavated trenches that end up with very high amount of transportation activities and this increase the share of transportation in TETP results. In Fig. 7, calculated environmental impact results for the smallest and biggest pipes (Ø110 PN10 and Ø355 PN10, respectively) laid are given to present this clearly.

Discussion and Conclusion

In this study, life cycle assessment of pipeline component of a water supply system is conducted. According to the contribution analysis of the results, manufacturing processes is determined as the hot spot of the study for the considered system boundaries, which was selected using cradle-to-gate approach. To the best of our knowledge, this study is a first attempt of LCA of a water supply line constructed in Turkey. It provides useful information for construction industry in terms of showing environmental impacts and environmental hotspots of the considered systems as well as presenting a case study for LCA practitioners. It would be of interest to look into other life cycle phases of this case study by expanding the system boundaries to include Operation and Maintenance and End-of-Life phases. Besides, refining the LCI by including exact transport distances, considering disposal of all of the construction wastes and using a local database developed for Turkey are some important factors to increase quality of the conducted work. Thanks to LCA, which is an iterative methodology, this can be realized in the future if required data and databases are obtainable.

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