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Life cycle sustainability analysis (lcsa) of polymer-based piping for plumbing applications

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Life Cycle Sustainability Analysis (LCSA) of Polymer-Based Piping for Plumbing Applications

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An Honors College Project Presented to

the Faculty of the Undergraduate

College of Engineering

James Madison University

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by Andy Jhon Rivas Bolivar

May 2017

Accepted by the faculty of the Department of Engineering, James Madison University, in partial fulfillment of the requirements for the Honors College.

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PUBLIC PRESENTATION

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Abstract

Water conveyance systems play a critical role in modern developed areas. Polymer pipes have been used for about a century, and their convenient physical properties have positioned polymers as the leading material in the piping industry. Having such influence in the market means that changes in current material selection and manufacturing could lead to significant reductions in the footprint associated with their products. Currently, there are no comparative lifecycle assessments that evaluate the different polymer selections commercially available, which makes it hard to determine what products have the least impact on the environment. Understanding how such impacts are relative to each other could lead to conscious customer material selection, and therefore, a reduced negative influence on impact categories such as human health, global warming, ecosystems quality, and natural resources depletion.

This study considered nine commercially available materials used for water conveyance: Chlorinated Polyvinyl Chloride (CPVC), Polybutylene (PB), High Density Polyethylene (HDPE), Cross-Linked Polyethylene (PEX), Polyvinylidene Difluoride (PVDF), Acrylonitrile Butadiene Styrene (ABS), Polyvinyl Chloride (PVC), Unplasticized PVC, and Polypropylene (PP). Two different groups were created to understand impact: products used for waste water conveyance (ABS, PVC, UPVC, PP, HDPE, PEX) and those used for drinking water distribution (CPVC, PB, HDPE, PEX, PVDF). To conduct this study, the LCA software tool Simapro 8.0.2 was used to model a cradle-to-gate comparative approach that took into consideration raw material extraction, polymerization, and processing of polymer resins to manufacture pipes. The Ecoinvent 3.01 libraries were used to compile empirical data from the pipe industry in countries all

around the world, which was evaluated using the Impact 2002+ and EPD 2008 LCA methods. External Environmental Product Declarations (EPD) played an important role as complementary sources of information for data not available on the Ecoinvent libraries.

Material impact was measured using various impact categories, and no material demonstrated lowest impact across all categories. Category prioritization would play a critical role in deciding materials based on what impacts are considered “more important” than others. Since no categories were prioritized in this study, footprint trends were used to provide the most appropriate material recommendation. In the wastewater group, PP demonstrated the lowest impact through most categories, while in the drinking water group, PB exhibited the lowest impact in all but one category. HDPE/PEX made a good second choice within both the drinking and wastewater group categories, while the rest of the materials seemed to have considerably higher impacts. Although data limitations encountered while developing the comparative assessment led to making some assumptions, the results from the study provide a good basis to recommend PB, PP, HDPE, and PEX as the most environmentally conscious material selections, without considering regional or national context.

Introduction

Increasing human needs and waste have led to the development of networks capable of conveying different types of fluids in an accessible manner. Such networks are known as plumbing systems, and their most common applications include potable water delivery, waste removal, and fuel gas conveyance. Early plumbing systems relied mainly on slope for fluid transport, and used materials such as clay, lead, and hollowed logs for conveyance. However, as manufacturing processes modernized, materials such as steel, copper, and polymers began playing a dominant role in piping applications (Kavanaugh, 2010). From such materials, polymers have become highly demanded in the plumbing industry due to their benefits which include corrosion resistance, cost-effectiveness, long-term performance, light weight, and ease of manufacturing. The following subsections discuss in further detail the motivation for conducting a study on polymers used in plumbing applications.

Problem Statement

As humans develop a necessity for more complex infrastructure and systems that make their lives easier, industries strive to make profit by manufacturing whatever is needed. The polymer industry has grown tremendously since the early 20th century (Mainland HS, 2010), and now is one of the major provider of a reliable and cost effective alternative to traditional metal piping. As industries grow along with improved technology, more effective methods for large scale product manufacturing, energy efficiency, and product functionality are developed. However, such advancement in technology has not always taken into consideration the impacts associated with product manufacturing. There were times when humans were not as conscious of their impacts as they are today, and it was not until the late 20th century that society began to think of how human activities were having an impact on the environment (Sustainable Development Commission).

The term we generally think of when evaluating impact is sustainability, and it is believed to have been introduced through the concept of overpopulation, as addressed in theories such as The Tragedy of the Commons. In this theory, a shared-resource community represents how self-interests can lead to resource mismanagement and depletion, eventually resulting in negative impacts at economic, social, and environmental levels (Sustainability for All). Although there has always been ongoing progress in terms of technology development, this development did not always take into consideration associated impacts, which has contributed to infrastructure and plants that are hardly adaptable to new technology. Impact analysis plays an active role in product and service development throughout the engineering design process. The Life Cycle Assessment (LCA) is a systematic tool that helps us evaluate the impacts of a product throughout all stages of its life (Global Development Research Center). In this study, an LCA is applied to provide an estimate of the impacts associated with the products studied.

One may wonder how current pipe manufacturing is causing any impact on us. First, the manufacturing processes associated with polymerization and molding not only require large amounts of energy, which is typically derived from fossil fuels, but also include the addition of chemicals to enhance its properties under specific conditions. Now, the main issue associated with these processes are the long-term impacts on our environment. The additives used in manufacturing processes combined with high temperatures result in the emissions of greenhouse and toxic gases, which add up to the harmful toxins that synthetic polymers continuously secrete over their lifetimes. Polymer manufacturing processes may include oil, chlorine, and carcinogenic additives that can act as cumulative toxins, posing potential health threats to those exposed. On the other hand, polymers take several years to degrade, so they will maintain their firm shape and break down through granulation (King, 2017).

Purpose and Objectives

The purpose of this thesis will be to conduct a life cycle analysis of nine different polymer-based pipes to determine their impacts on the environmental dimension of sustainability. The impacts associated with an industry as large as the polymer piping industry are believed to be enough to have significant effects on the natural environment; thus, conducting a comprehensive assessment of current processes could lead to more conscious manufacturing, material selection, and product utilization. Based on preliminary research, the most commercially common polymer-based pipes were narrowed down to acrylonitrile butadiene styrene (ABS), chlorinated polyvinyl chloride (CPVC), polybutylene (PB), high density polyethylene (HDPE), cross-linked polyethylene (PEX), polypropylene (PP), polyvinyl chloride (PVC), polyvinylidene fluoride (PVDF), and unplasticized polyvinyl chloride (UPVC). Each of these products is not only processed uniquely, but is used for different purposes in the plumbing industry, thus having varying impacts throughout their lifecycles (Chasis, 1988). This thesis was conducted with three main objectives in mind:

1. Conduct a unique life cycle assessment in which parameters, assumptions, and outcomes are strictly related to the commercial polymer-based products of interest.
2. Identify major impacts associated with the products used for drinking and waste water conveyance. each of the products of concern.
3. Based on data interpretation, provide recommendations regarding material selection within the studied alternatives.

Broader Impacts

In this study, the focus will be our ecosystem, which not only includes the natural environment, but the organisms living within it. Impacts on our communities were studied based on environmental quality and natural resource parameters. Parties of interest to this study focused on two main groups, pipe manufacturers and pipe users, with each group having an influence over the other's decisions. The outcome of this study could identify significant emissions associated with manufacturing certain products, leading to more environmentally conscious material selection. However, the main objective of this study was to promote long-term well-being of our ecosystems through more sustainable pipe systems having reduced emissions, and thus less of an impact on our environment and health.

Literature Review: Materials Processing and Polymer Pipe Manufacturing

Raw Material Processing

The term polymer is used to describe large molecules made up of thousands of atoms chemically bonded together in a regular pattern. Polymers tend to form in chain-like networks, but they can form complicated structures as well. The part of the polymer that is repeated to complete polymer chains is known as a repeat unit (University of Illinois Urbana-Champaign). Such repeat units are formed of single molecules called monomers. The behavior of a polymer is determined by how monomers are arranged in its repeat units, as well as by what types of atoms composing them.

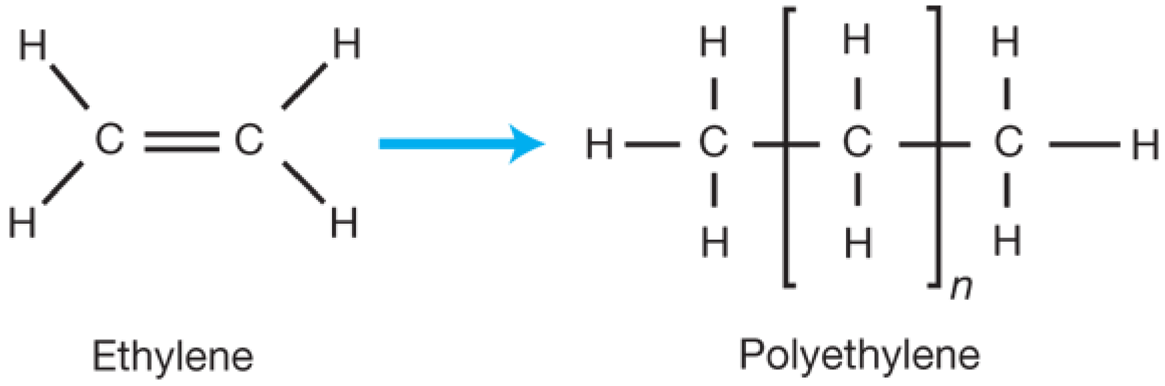


Figure 1: Monomer and Polymers Graphical Example PE (Sharpe, 2015)

Before a polymer product can be manufactured, raw material must go through various processes to become workable enough. For purposes of this assessment only man-made polymers will be studied, which are generally known as synthetic. The raw materials from which polymers are manufactured include paraffin, lubricating oil, and other products obtained from crude oil refining (Stephens Plastics Mouldings). Monomers are derived from these oil-based products and linked together through a process known as polymerization (if condensation used). The type of polymerization of main interest for the polymers used in plumbing is the addition polymerization method, also known as chain-growth polymerization.

An addition polymer is the result of a reaction where many monomers are bonded together experiencing no loss of atoms or molecules (Polymer Science Learning Center, 2005). The process consists of linking molecules through double or triple carbon bonds. The process is first started by an initiator, which is usually an organic compound causing unsaturated monomers to link up by the breakage of extra internal bonds. This breakage leads to a chain propagation up until termination, where an active site transfers to another chain, forming the branching. Finally, a combination termination or disproportionation method is used to end the reaction. The most common addition polymers result from unsaturated monomers, and include polymers such as PE, PP, HDPE and PVC. Addition polymerization can be the result of bulk, coordination, suspension, emulsion, and free radical polymerization methods (University of Wisconsin-Madison).

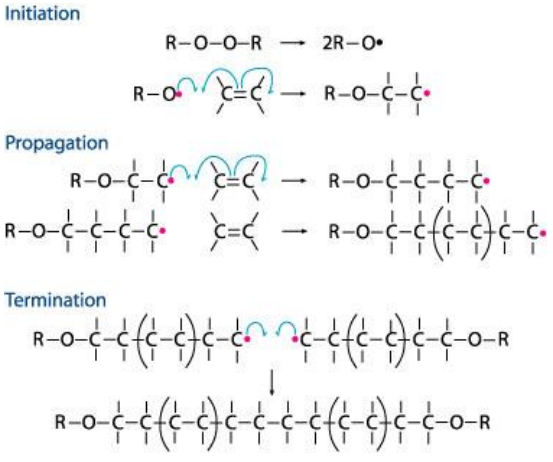


Figure 2: Addition Polymerization Process. (Bishop, 2013)

Bulk Polymerization

Bulk polymerization is the simplest method in terms of its formulation since it does not require any solvents or dispersants in its reaction to break up substances into droplets or to promote dilution. In fact, the main reason why bulk polymers differ from other reactions is that the main input to the reactor involves essentially pure monomers; the amounts of catalysts and additives are very small (Stevens, 2016). For chain-growth reactions, the process is generally exothermic; the heat evolved can make the reaction temperature hard to control. Bulk reactions are not easily stirred due to the high viscosities associated to the high molecular mass of the polymers formed. Although bulk polymerization can be used by polymers requiring very particular characteristics such as clarity, it can be used to produce other polymers of interest for this study such as PEX (National Oilwell Varco L.P., 2015).

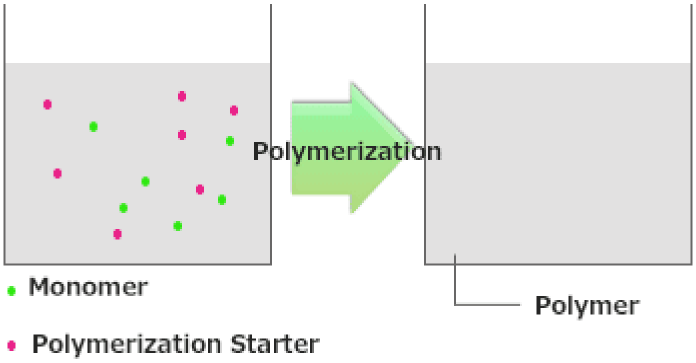


Figure 3: Bulk Polymerization (Gowdham)

Coordination Polymerization (Ziegler-Natta)

Coordination polymerization is a type of addition polymerization where a monomer is added to a growing larger molecule through an organometallic active center. Coordination polymers are composed of monomers added to growing macromolecules to form an extended chain. During the 1960’s, coordination compound catalysts were discovered for use in addition polymerization processes. Such catalysts are known as Ziegler-Natta, and they control the tacticity of polymers in a reaction, which promotes the linear order within the polymer chain (Ebewele, 2000). Therefore, coordination polymers tend to be linear and have much higher molecular densities, which improves physical properties such as tensile strength while allowing for higher crystallinity (Purdue University). Coordination polymerization allows more control over the polymer, enhancing properties such as rigidity and permeability, as evidenced by the higher density of HDPE relative to LDPE.

Suspension Polymerization

Suspension polymerization is a heterogenous-radical polymerization method that allows the mixture of one or more monomer types in a liquid, generally water, through mechanical agitation (stirring) (Gooch). This process requires the addition of stabilizers and a monomer-soluble initiator. The resulting polymers can be in the form of beads or pearls, which are easily separated from the liquid when stirring is stopped; these beads are typically the ones dried and packed for shipment (Stevens, 2016). This polymerization process is used in the production of the PVC family.

Emulsion Polymerization

One of the most commonly used methods to produce vinyl polymers is emulsion. This method involves the formation of a stable monomer in water using an emulsifier (agent that allows droplet dispersion and stability). When the chemicals are mixed, monomer droplets spread evenly along the water phase, and remain like that because of the emulsifier (Stevens, 2016). Smaller monomer droplets known as micelles begin to form, which are surrounded by initiator and other reactive molecules. Initiators dissolved in the water migrate into micelles to begin the polymerization process. The reaction ends when second radical initiators diffuse into swelling micelles, which results in high molecular densities. Formulating the mixture for emulsion is much more complex than in other methods, thus making its purification more difficult (Conjecture Corporation, 2017).

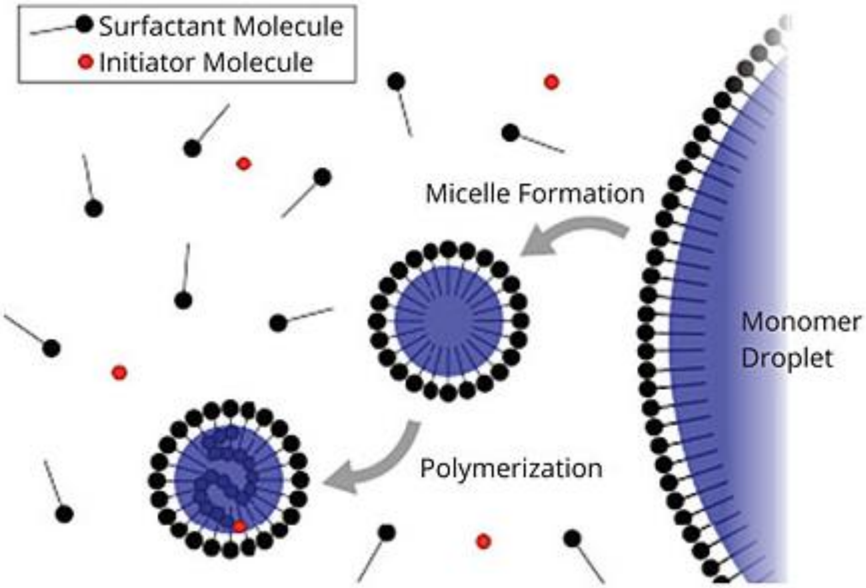


Figure 4: Emulsion Polymerization (Palmer, 2012)

Free-Radical Polymerization

Free-radical polymerization produces polymers by the addition of free radical building blocks. It is one of the most common reactions, and is used to make polymers out of vinyl monomers. The process consists of three fundamental steps: initiation, propagation, and termination (Polymer Science Learning Center, 2005). Building blocks can be formed by reacting initiator molecules that create the polymer chain. Free radical polymerization is one of the most versatile forms of polymerization, allowing simple reactions of polymeric free radical chains and other substances. In free radical polymerization, chain transfer can take place, which is the transfer of growth active site from an active chain to a previously inactive one (Polymer Properties Database, 2015). Polymers created from this method include mainly the polyethylene family.

Polymer Manufacturing

The outcome of the polymerization step is typically polymers in the form coagulated pellets, which are sent out to larger plants generally set up outside the US. At the manufacturing plants, the workable polymer pellets receive further treatment such as heating, rolling, and molding so that they can have the shape, size, and properties desired for the pipe products. Since this study is focused on piping used in the plumbing industry, there will be an emphasis on the manufacturing techniques used to produce ABS, CPVC PB, HDPE, PEX, PP, PVC, PVDF, and UPVC pipes. The methods used to treat polymers at manufacturing plants include compression molding, injection molding, extrusion molding, and thermoforming.

Compression Molding

Compression molding is a high-volume, high-pressure method used to mold high strength objects. This process basically transforms granular preheated material into molded shapes by placing it in an open mold cavity and then closing it. Closing the mold adds the force required for the polymer to flow into all areas of the cavity, and then it is heated to at least 300°F. This step begins the curing, where thermosets undergo an irreversible chemical reaction resulting in a highly cross-linked molecular structure (Reliance Engineering, 2015). As opposed to other methods, residual material left behind must be disposed since cured thermosets cannot be reground or reprocessed. Once mold cavities are filled, the part must cure to a solid shape. Because there are no runner or gate systems in a compression mold, product mechanical properties tend to be better than the same part molded by injection (D&M Plastics Inc).

Injection Molding

Injection molding is one of the most commonly used methods in plastic manufacturing. The process consists of granular material fed into a heated container by a reciprocating screw, which then undergoes a melting process. As the granules are pushed forward, the molten plastic is forced through a nozzle, allowing it to enter mold cavities through a gate-runner system (XCentric Mold and Engineering). The mold, usually made of steel or aluminum, remains at a constant temperature so that the material solidifies as soon as the mold is filled up. Injection molded parts tend to have high precision, low costs in term of labor, minimal losses, and little need to finish parts after the process is done. However, they could represent an expensive upfront tooling investment cost (3D Systems Inc, 2017).

Extrusion Molding

Extrusion molding is another widely-used process across the plastic manufacturing industries. The process involves the shaping of plastics using a rigid frame called pattern. This method is generally used to create tube-shaped objects from polymer pellets or granules (Flite Technology). The process takes place in an extrusion machine, where a motor turns a screw, feeding plastic stored in a hopper through a heater. The plastic granules are then molten into liquid, and pushed through a die, forcing the material into a tube shape, which dimensions depend on the die used. This constant cross-section helps keep cost down associated with finishing in most cases (Efunda Inc, 2017). Extrusion molding is used to manufacture mostly thermoplastics such as ABS, PE, PP, and PVC. This method is very cost-effective due to its low operation and upfront costs; however, parts are just moderately precise while the production speed is slow compared to other methods.

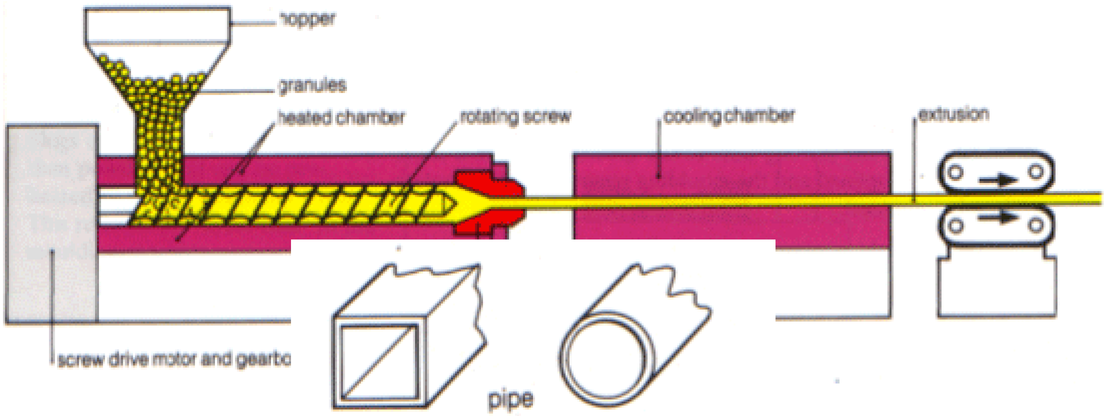


Figure 5: Extrusion Molding (AV Plastics)

Thermoforming

Thermoforming is a plastic manufacturing process that produces parts by heating up a thermoplastic sheet until its softening point, stretching the sheet over a mold, and allowing the plastic to cool and solidify to the desired shape (Pioneer Packaging Worldwide, 2015). The sheet is then clamped into a holding device, softened a second time, and pressed using a vacuum/air pressure tool (Custom Parts Net, 2017). Once it is solid, excess material is trimmed away and the created part is removed. The advantages of thermoforming include its low tooling and engineering costs as well as it turnaround time, making it ideal for prototyping and low-volume production of PVC, ABS, PP, and PE (Techniform Industries).

Products of Concern

As defined in the scope of this life cycle assessment, there will be a focus in Acrylonitrile-Butadiene-Styrene (ABS), Polybutylene (PB), High-Density Polyethylene (HDPE), Cross-linked Polyethylene (PEX), Polypropylene (PP), Polyvinyl Chloride (PVC), Unplasticized Polyvinyl Chloride (UPVC), Chlorinated Polyvinyl Chloride (CPVC), and Polyvinylidene Fluoride (PVDF). The following subsections discuss each of these materials in more detail, including their common uses in the plumbing industry, manufacturing background, and general properties.

Acrylonitrile-Butadiene-Styrene (ABS)

ABS is a copolymer of acrylonitrile, butadiene, and styrene. As a thermoplastic resin, it liquefies easily, and can be recycled through injection molding. In addition, ABS does not present an ordered crystal structure (amorphous) and is known to be tough, hard, and rigid. ABS is commonly manufactured by through an emulsion process; it is important to note, however, that since ABS is commonly recycled, it can be created from itself (ABS Material, 2012).

ABS characteristics include a high resistance to corrosion due to chemical damage, its considerable ease to machine, and lower melting temperature than most plastics, which makes it easier to be manufactured by injection molding (although modern process such as 3D printing and fused deposition molding) (Creative Mechanisms, 2016). Since it has a low melting point, ABS can be used only in low-heat applications. In terms of price, it is quite inexpensive, which makes it a much more affordable choice compared to other plastics. As far as health concerns, it is not known to be a carcinogen or have a direct health impact caused by regular exposure.

Within its pipe applications, ABS resistance to chemicals allows it to convey a wide variety of fluids. However, it is known to show degradation in the presence of chlorinated hydrocarbons, as well as deformation when exposed to UV radiation from the sun. In addition, it is known to generate high amounts of smoke when burned (Diffen). Due to its limiting properties, it cannot be placed above ground, so regulations require the addition of pigments or the painting of a layer of latex on these pipes. ABS is easy to install and commonly found in drain-waste-vent sewers.

Polybutylene (PB)

PB is a saturated semi-crystalline polymer produced from the polymerization of 1-butene using catalysts. PB is known to have a high molecular weight, and can be easily manufactured by compression and injection molding, welding, and extrusion. Due to its crystalline structure, it is resistant to the hydrostatic pressure caused by fluids, and shows a good elastic recovery. PB is resistant to chemicals such as oils and acids, however, it has low resistance to chlorinated hydrocarbons and oxidizing acids. PB had been used mainly for cold and hot potable water transport and heating/cooling networks; however, due to leaks associated with degradation in the presence of chlorinated water, it is no longer sold or allowed in buildings in the US (Polybutene

Piping Systems Association, 2006). The reaction within PB pipes seemed to develop at a rapid rate, and since it occurs within the pipes, it cannot be easily assessed, causing sudden leaks or bursting.

Polyethylene (PE)

PE is a thermoplastic polymer that consists of several ethylene monomers, which consist of two carbon atoms with two hydrogen atoms attached to each. PE is a stable molecule, and it polymerizes only when it is in contact with catalysts, and is generally processed by coordination polymerization. PE has a somewhat low strength and rigidity, but has high ductility and impact strength. It is composed by saturated, nonpolar hydrocarbons, which tend to crystallize in most of its forms (Polymer Science Learning Center, 2016). PE has a very good chemical resistance against strong acids and oxidants, but can become brittle when exposed to UV radiation, which is often solved by the addition of carbon black. Generally, PE is classified based on its branching, crystal structure, and molecular weight. In plumbing applications, the most relevant types are high-density polyethylene (HDPE) and cross-linked polyethylene (PEX).

High-Density Polyethylene (HDPE)

HDPE consists of a structure mostly linear, where molecules are well-packed, presenting high intermolecular forces. It is most commonly the result of Ziegler-Natta polymerization, which facilitates control over the branching due to the formation of free radicals that form a linear-type network (ISCO). HDPE has a high tensile strength, malleability, and an ability to withstand temperatures up to 248°F. It is commonly used in underground piping due to its chemical resistance, non-toxicity and long term designs. HDPE works as a very good non-corrosive insulator, and is FM approved to be used for municipal and industrial piping networks (American Chemistry Council, 2015).

Cross-Linked Polyethylene (PEX)

PEX consists of a cross-linked structure formed during an extrusion process. When manufactured for pipework systems, it is generally derived from HDPE, changing it from a thermoplastic to thermoset as crosslinks form. The crosslinking of PEX improves the thermal resistance of its base polymer, as well as other properties such as chemical resistance to dissolution, impact resistance, tensile strength, and brittleness (Tradesmen Supply LLC, 2006). PEX is generally used in pipework systems such as water transport, sewage, and heating/cooling in buildings.

During the last decades, PEX has been increasingly used as an alternative to materials such as PVC and traditional copper pipes. PEX pipes have become quite popular due to their cost effectiveness, non-corrosive properties, ability to carry both hot and cold fluids, and their acceptance in plumbing codes within the US (The Family Handyman) However, they are known to have issues such as degradation from sun exposure, odors in potable water, and troublesome adjustment to existing plumbing systems.

Polypropylene (PP)

PP is a thermoplastic polymer manufactured from the monomer propylene through an addition reaction. PP can be manufactured through CNC, extrusion, injection molding, thermoforming, or crimping. It can be easily copolymerized with other polymers which can significantly improve its properties (Sato, 2009). At room temperatures, PP is known to be highly resistant to strong oxidants and acids. At high temperatures, however, PP tends to oxidize, which required the addition of antioxidants during manufacturing.

Although the properties of PP generally depend on its molecular distribution and crystal structure, it is known to present a good range of elasticity, toughness, and fatigue resistance. On the other hand, it can experience degradation from UV radiation from the sun, for which its external use is limited without the addition of additives. The use of PP in piping is not very popular in the US, even though it is widely used in Europe (National Association of Realtors, 2017). PP pipes are rigid, durable, and have history of being safe. Unlike other materials, PP is not joined with chemicals, but requires permanently mating ends through heat and fusion.

Polyvinyl Chloride (PVC)

PVC is a synthetic plastic polymer created from its monomer vinyl chloride. It is known to be a solid and chemically stable substance produced by suspension, emulsion, and bulk polymerization. PVC pipe systems generally convey water and wastewater due to its chemical resistance, and non-toxicity (Titow, 1984). Currently, building codes approve the use of PVC pipe, although not generally for hot water systems, since it destabilizes at about 280°F. PVC is widely used in piping, and its advantages include being lightweight, flame retardant, good elastic properties, and easiness of installation. On the other hand, temperature limits its strength, and can also become easily crackable (Smith, 2016). Other forms of PVC usually used in plumbing applications include Unplasticized Polyvinyl Chloride (UPVC) and Chlorinated Polyvinyl Chloride (CPVC).

Unplasticized Polyvinyl Chloride (UPVC)

UPVC is also known as rigid PVC and has been used during the last decades as a replacement of traditional metal pipes used for plumbing and drainage. It is the most commonly used plastic used for pipe purposes due to its high opposition to chemical erosion. The main technical aspect that makes UPVC unique is that it does not contain the additives included in PVC. UPVC generally conveys waste pipes, drainpipes, and downspout, and its beneficial properties include being flame retardant, highly UV resistant, cost effective, stiff and very strong. In addition, it works well in a wide range of temperatures and its inner smoothness allow for easier water flow (Diffen). It is important to note that neither PVC nor UPVC are used for drinking water distribution.

Chlorinated Polyvinyl Chloride (CPVC)

CPVC is a thermoplastic resulting from the free-radical chlorination of polyvinyl chloride. It consists of two carbon atoms double bonded, and a hydrogen and chlorine atom single bonded to each carbon. CPVC is very resistant to degradation by chemicals, safely transporting potable water. Like ABS, CPVC is not resistant to UV radiation from the sun, needing additional stabilizers and pigments. Just like most polymers, CPVC has a long expected time of useful performance.

Although CPVC is a thermoplastic, its melting temperature is considerably high (about 200°F) and its chemical composition containing chlorine makes it fire-retardant, which also develops a greater bacteria prevention within the pipes. CPVC is commonly used to convey both cold and hot water since its inherent insulation helps lower condensation within pipes, maintaining fluids at relatively stable temperatures over time (PVC Pipe Supplies). Due to its temperature advantages over other materials, CPVC has become a requirement in many building codes instead of other choices.

Polyvinylidene Fluoride (PVDF)

PVDF is a semi crystalline fluorinated thermoplastic that can be synthesized from its monomer, vinylidene fluoride, by free radical polymerization. PVDF is known by its outstanding resistance to acids, alcohol, oxidizing environments, and resistance to radiation, unlike most polymers. In addition, it has a good aging resistance associated with other properties such as being fire resistant and self-extinguishing (Plastics Europe). PVDF is FDA compliant, and due to its non-toxicity can safely be in contact with potable water. Common applications include the conveyance of ultra-pure water and sensitive chemicals. Additional properties of interest include benefits such as torsion, compression, and tension resistance, low weight, low thermal conductivity, and abrasion resistance (Porex Corporation).

Table 1: Summary of Materials Main Properties

Material	Main Properties
ABS	Tough, hard, rigid, corrosion resistant to chemicals, low melting temperatures, used for low heat applications, deforms under UV radiation, commonly used in sewer systems.
PB	High molecular density, good elastic recovery, high fluid pressure resistance, chemical resistance to oils and acids, commonly used in waste water systems.
PE	Low strength and rigidity, high ductility and impact strength, good chemical resistance, becomes brittle when exposed to UV radiation.
HDPE	Higher tensile strength and malleability, handles high temperatures and can be used underground due to its chemical resistance.
PEX	Derived from HDPE, non-corrosive, improved thermal and chemical resistance, high impact and tensile strength.
PP	Strong to oxidants and acids (except at high temperatures), high elastic, tough, and fatigue resistance. Requires permanent mating ends using heat and fusion.
PVC	Chemical resistant, non-toxic, lightweight, flame retardant, elastic, crackable under high temperatures, used for waste water applications.
UPVC	High opposition to chemical erosion, UV resistant, stiff, strong, flame retardant, used for wastewater applications.
CPVC	Not resistant to UV, flame retardant, extremely high bacteria prevention, hot & cold water performance, stable under varying temperatures. Can be used for drinking water conveyance.
PVDF	Outstanding resistance to acids and oxidants, self-extinguishing, fire retardant, high torsion, compression, abrasion, and tension resistance. Used for ultra-pure water applications.

Methodology

Products as found in stores are the result of a process network with varying inputs, outputs, and requirements. To measure to what degree products have an impact in our surrounding, it is critical to understand the raw material and energy requirements within their network. Measuring impact is not limited to product manufacturing; it also includes activities such as transportation, use, and disposal, all of which contribute to environmental impacts. The study of the energy and material flows associated with product impact is generally known as life cycle analysis (LCA), a systematic tool used to evaluate impacts through all life stages. LCAs generally consist of four main sections that define the study: goal and scope, life cycle inventory (LCI), impact assessment, and final interpretation (Williams, 2009). In the following subsections, the goal, scope, LCI, and other methods used in this study are discussed in further detail (see Figure 1 for a summary).

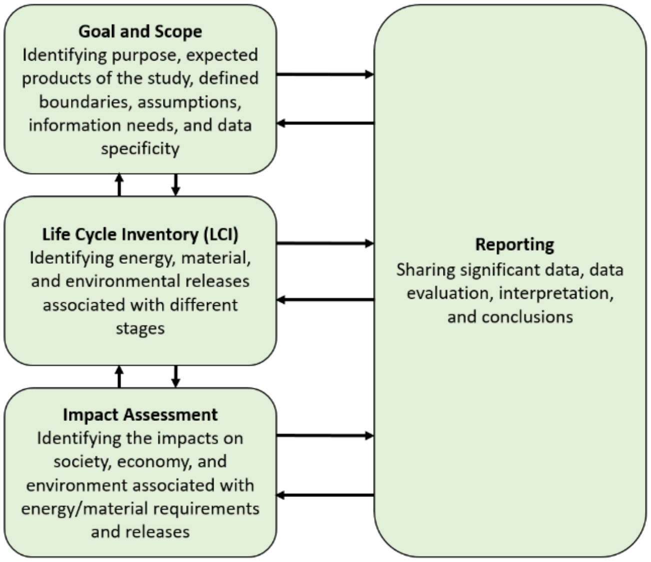


Figure 6: LCA Phases

Goal and Scope

The goal of this study is to determine how the manufacturing of polymer pipes used in both drinking and waste water conveyance systems has an impact on the environment. The results of this study will provide an increased understanding of what such impacts are and what they represent. The audience for this LCA consists of the pipe manufacturing industry, pipe users, and interested scholars. The study was conducted by a senior engineering student at James Madison University as part of an honor research thesis. A JMU professor with expertise in lifecycle impact assessment as well as in environmental and chemical engineering worked as the main advisor of the study. Access to library databases and educational software licenses were granted, facilitating research and life cycle analysis by using the software tool Simapro 8.0.2.

In this comparative LCA, nine different polymer products were studied. Since not all pipes are used for the same purpose, products were grouped into two categories: pipes used for potable water (CPVC, PB, HDPE, PEX, PVDF), and pipes used for wastewater (ABS, PVC, UPVC, PP, PE, HDPE, PEX). This study focused on the energy/material requirements as well as on the emissions generated throughout the manufacturing process. A cradle-to-gate approach was chosen, beginning with the extraction of raw materials and continuing through the polymerization and molding processes required to make the product as they are sold. Although some products are recyclable, this study neglected this step since collection, transportation, and operational stages of recycling are not within its scope. A fixed volume of 100 cubic inches of fluid was used as the functional unit. The required volume of material was determined based on existing commercial pipes and their use. Generally, schedule 80

1-inch pipes are used for potable water conveyance and schedule 80 1.5-inch for wastewater. Material volume required was determined to be 88.8 cubic inches for pipes conveying potable water and 60.4 cubic inches for pipes conveying wastewater (Appendix 1).

Most data used in this LCA was obtained from the Ecoinvent 3.01 libraries available in Simapro. Complementary information was researched as needed to define processes and assemblies that were not available in Simapro. Parameters were established so that there was little to no bias between the products studied. The level of uncertainty of this study is estimated to be within 5% for the results obtained by using Simapro. This LCA is not based on a specific company, group of users, or location since transportation and usage assumptions can cause results to vary significantly. Geography, in combination with data availability, posed a limitation to this study, which is the main reason why a cradle-to-gate approach was preferred, avoiding extensive assumptions that would increase the uncertainty of results.

Life Cycle Inventory

Literature review played a critical role in how the goal and scope of this project was defined. This LCA followed a cradle-to-gate approach, which means that distribution, use, and the end of life stages of the products were not considered. The overall pipe manufacturing process studied has been outlined in Figure 2 presented below.

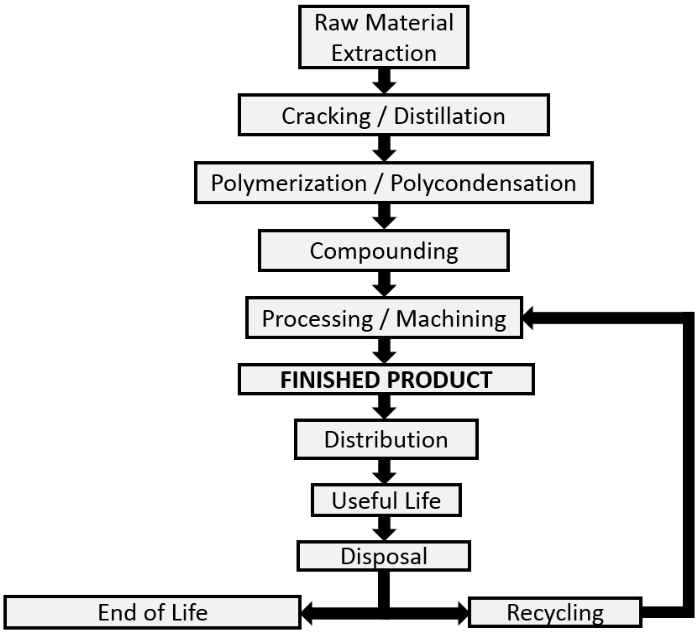


Figure 7: Pipe Manufacturing Process Diagram

Although the step processes for each product vary, Figure 2 provides a reasonable overview of the general process network for polymer pipes. The cycle begins with the extraction of raw material, generally derived from natural gas and oil after a cracking process. The result of this process is generally monomers in the form of pellets, which are sent to polymerization locations. After undergoing high temperature chemical reactions, these pellets yield the base resin we know as polymers. After or during polymerization, compounding occurs by the inclusion of additives to control physical properties of the products. Finally, the finished pipe results from a last heating and molding process where the required product shape and dimensions are obtained. The products are detailed, packed, distributed, used, disposed, and some of them recycled under circumstances that rely tremendously on users, companies, and locations.

Research on the pipe manufacturing process allowed identifying the inputs and outputs found in Table 2.

Table 2: Material, Energy, and Emissions Flows

Type	Input	Output
Material	Oil, natural gas, additives, heating and molding machinery, catalysts and chemical facilitators	Feedstock, monomers, polymers, polymer pipes
Energy	Thermal, electrical, chemical, mechanical, potential, human	Potential
Emissions and Waste	-	CO2, CH4, N2O, HFCs, PFCs, SF6, HCFC

Additives, facilitators, and catalysts groups include hundreds of substances that vary widely among products. On the other hand, emissions and waste were narrowed down to those having the most influential impact on the damage categories studied. The emission of toxic fumes and liquid waste is both energy and process dependent. Simapro databases consider all the emissions associated with the products studied and use defined LCA methods to quantify impact through mid-point categories. After running multiple computations on Simapro, the most relevant impact categories were determined to be:

- Global Warming/Climate Change
- Ozone Depletion
- Photo-Chemical Ozone Creation

- Acidification of Soil and Water
- Eutrophication
- Human Health
- Ecosystem Quality
- Resources

Data Collection and Interpretation

Collecting and analyzing data can be a complex task considering that methods vary considerably from source to source. Simapro is an LCA software package developed by Pre-sustainability, and the leading sustainability tool currently available (Pre Sustainability). The software allows users developing entire networks and having an insight and control over unit processes and databases. Before summarizing how this study was set up using Simapro, it is important to understand the different sections available within the software to develop an LCA:

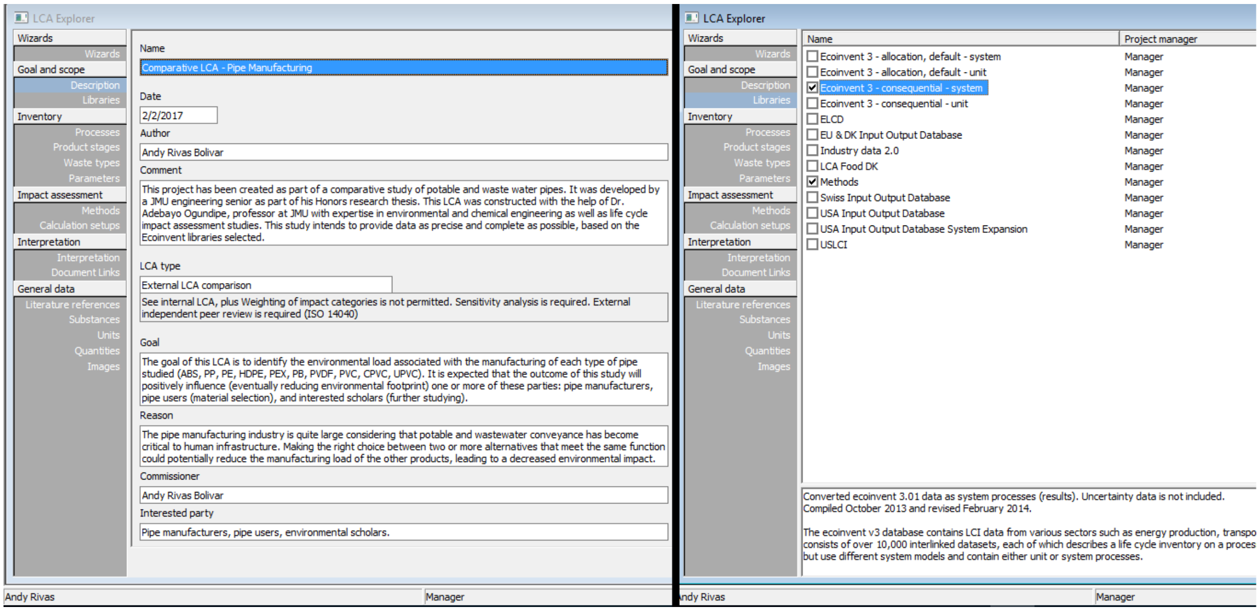
Goal and Scope: This section is used to define the nature of the project. It includes details such as author(s), LCA type, dates, functional units, project description, and other more specific characteristics of the study. In addition, libraries (large collections of data) are selected from the goal and scope section, which is key to defining geographical origin, completeness, and age.

Inventory: The inventory section is the most comprehensive of all. Within the inventory, material, energy, transportation, use, among other processes are defined in detail. Product stages such as assemblies, lifecycle, waste management, and reuse can be set up within this section.

<u>Impact Assessment:</u> In this section, existing life cycle impact methodologies can be selected or new ones can be defined. This is a critical step on deciding how input will be processed by Simapro. Impact assessments are the result of predefined impact and damage categories, normalization, and weighting factors that support data processing.

<u>Interpretation & General Data:</u> The last two sections are designed to allow documentation of outcomes, contributions, and references. It also contains quantity, unit, and substance configurations that are used during data processing (note that these should be defined at an earlier stage of the study).

The goal and scope section was filled in based on what had been defined earlier in this section. Some of the subsections, however, required the use of very specific language to avoid any confusions. Since this study is not to be used within a company or organization and its only purpose is educational, it was defined as an external LCA comparison. The second part of the goal and scope consisted of libraries selection; which was critical since these define how data is obtained, where it comes from, and how it is displayed in the end results. The Ecoinvent libraries were selected based on their reliability and completeness. It was decided to use consequential libraries to consider the full share of impacts associated with making the product, which is key considering that by-products are not within the scope of this study. Equally important was the selection of a unit library, since it is not only desirable to understand what product has the most impact, but where these impacts come from within the manufacturing process. Figure 3 shows how the goal and scope section was filled out as well as the libraries and methods selected.



Name
Comparative LCA - Pipe Manufacturing

Date
2/2/2017

Author
Andy Rivas Bolivar

Comment
This project has been created as part of a comparative study of potable and waste water pipes. It was developed by a JMU engineering senior as part of his Honors research thesis. This LCA was constructed with the help of Dr. Adebayo Ogundipe, professor at JMU with expertise in environmental and chemical engineering as well as life cycle impact assessment studies. This study intends to provide data as precise and complete as possible, based on the Ecoinvent libraries selected.

LCA type
External LCA comparison
See internal LCA, plus Weighting of impact categories is not permitted. Sensitivity analysis is required. External independent peer review is required (ISO 14040)

Goal
The goal of this LCA is to identify the environmental load associated with the manufacturing of each type of pipe studied (ABS, PP, PE, HDPE, PEX, PB, PVDF, PVC, CPVC, UPVC). It is expected that the outcome of this study will positively influence (eventually reducing environmental footprint) one or more of these parties: pipe manufacturers, pipe users (material selection), and interested scholars (further studying).

Reason
The pipe manufacturing industry is quite large considering that potable and wastewater conveyance has become critical to human infrastructure. Making the right choice between two or more alternatives that meet the same function could potentially reduce the manufacturing load of the other products, leading to a decreased environmental impact.

Commissioner
Andy Rivas Bolivar

Interested party
Pipe manufacturers, pipe users, environmental scholars.

Name	Project manager
☐ Ecoinvent 3 - allocation, default - system	Manager
☐ Ecoinvent 3 - allocation, default - unit	Manager
☑ Ecoinvent 3 - consequential - system	Manager
☐ Ecoinvent 3 - consequential - unit	Manager
☐ ELCD	Manager
☐ EU & DK Input Output Database	Manager
☐ Industry data 2.0	Manager
☐ LCA Food DK	Manager
☑ Methods	Manager
☐ Swiss Input Output Database	Manager
☐ USA Input Output Database	Manager
☐ USA Input Output Database System Expansion	Manager
☐ USLCI	Manager

Converted ecoinvent 3.01 data as system processes (results). Uncertainty data is not included.
Compiled October 2013 and revised February 2014.

The ecoinvent v3 database contains LCI data from various sectors such as energy production, transpo
consists of over 10,000 interlinked datasets, each of which describes a life cycle inventory on a proces
but use different system models and contain either unit or system processes.

Figure 8: Goal and Scope and Libraries of LCA on Simapro

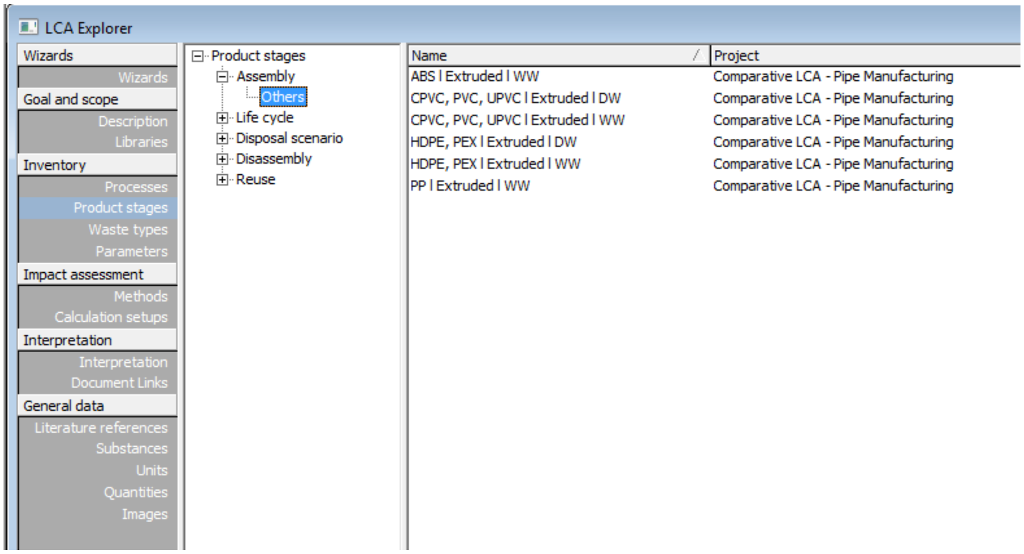
Once the goal and scope was defined, the LCA proceeded to the inventory section. In the inventory, one could see all the materials, processes, and waste available within the Ecoinvent libraries. The initial step was to compile all the materials desired. It was determined that some of the products/materials to be studied were not available within Ecoinvent and could therefore not be studied as initially planned. To solve this, some of the products to be studied were grouped based on their similarity. For example, UPVC and PVC granulates were assumed to be “the same” since the addition of plasticizers makes a relatively small difference in the overall impact of manufacturing the product. Products were the result of an assembly, where resin granulate inputs would undergo a molding process available in Simapro to yield the desired amount of final product. The following list summarizes the assumptions, decisions, and grouping made while setting up the assemblies on Simapro:

Groups to be studied:

- *Wastewater products*: ABS, PVC, UPVC, PP, HDPE, PEX
- *Drinking water products*: CPVC, PB, HDPE, PEX, PVDF

Material grouping and assumptions:

- *HDPE and PEX:* PEX is the result of cross-linking HDPE. Since cross-linking is not available in Simapro, these two products were grouped together as HDPE.
- *PVC and UPVC:* PVC and UPVC only differ in the addition of plasticizers. All polyvinyl available in Simapro already take plasticizers into account, therefore, it was decided to assume UPVC had the same characteristics as PVC.
- *CPVC and PVC*: CPVC contains a greater concentration of chlorine than PVC. Simapro does not contain the free radical chlorination reaction that PVC must undergo to produce CPVC. Therefore, it was assumed that CPVC had the same characteristics as PVC.



<table>
<tr><th>Name</th><th>Project</th></tr>
<tr><td>ABS | Extruded | WW</td><td>Comparative LCA - Pipe Manufacturing</td></tr>
<tr><td>CPVC, PVC, UPVC | Extruded | DW</td><td>Comparative LCA - Pipe Manufacturing</td></tr>
<tr><td>CPVC, PVC, UPVC | Extruded | WW</td><td>Comparative LCA - Pipe Manufacturing</td></tr>
<tr><td>HDPE, PEX | Extruded | DW</td><td>Comparative LCA - Pipe Manufacturing</td></tr>
<tr><td>HDPE, PEX | Extruded | WW</td><td>Comparative LCA - Pipe Manufacturing</td></tr>
<tr><td>PP | Extruded | WW</td><td>Comparative LCA - Pipe Manufacturing</td></tr>
</table>

Figure 9: Materials Grouping: Wastewater (WW) and Drinking Water (DW).

Other considerations:

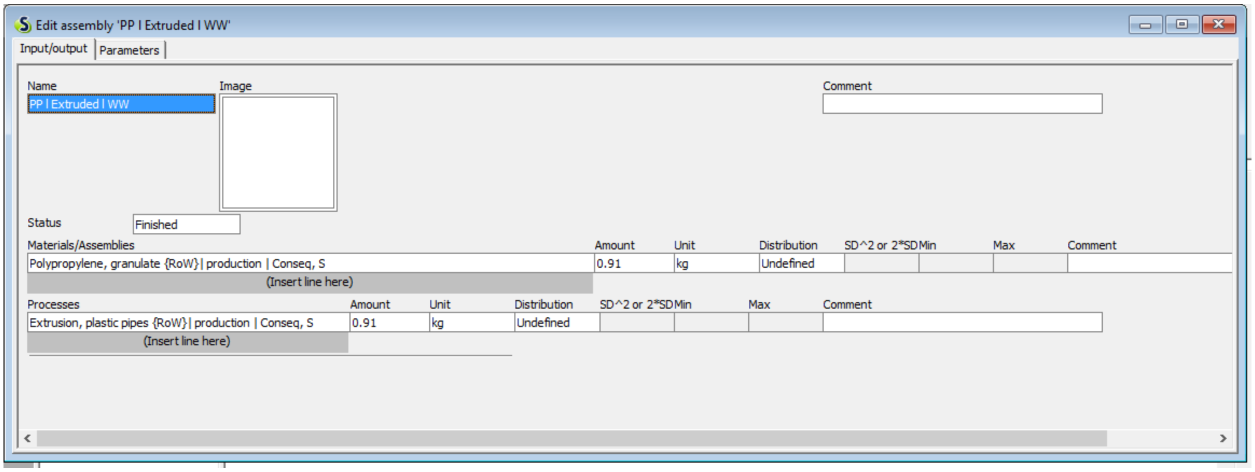
- Only materials within the transformation categories were considered because transportation factors for commercial purposes were not within scope of this study.
- Processes and materials have certain geographical location associated to them in the Ecoinvent libraries. The Rest-of-the-World (ROW) location was selected for all materials used in this study. ROW determines averages from all countries including uncertainty adjustments.
- Extrusion molding was the process selected for all materials for two reasons: 1) it is the most commonly used and 2) the rest of the polymer manufacturing processes available on Simapro are used for other product purposes such as bottles or smaller pipe parts such as elbows.
- Polymerization methods were selected based on both availability and commonality for each material.
- Mass of product to be analyzed was determined based on density known through research. The functional unit initially defined for this study allowed defining required mass output for desired volume of product (Appendix 2).

A summary of the selected materials and processes used in the LCA includes:

- ABS: granulate from emulsion polymerization
- PP: granulate from free-radical polymerization
- HDPE/PEX: granulate from free-radical polymerization

- PB: granulate or by-product could not be found on Simapro, no reasonable assumptions could be made. External research allowed finding environmental product declarations (EPD) on previous studies on a PB-1 pipe system.
- CPVC/PVC/UPVC: granulate from emulsion polymerization
- PVDF: granulate or by-product could not be found on Simapro, no reasonable assumptions could be made. External research allowed finding environmental product declarations (EPD) on previous studies on a PVDF pipe system.
- Extrusion: manufacturing process selected for all granulates studied.

Figure 10 provides an example of what a product assembly looks like on Simapro once all the assumptions are considered.



Name: PP I Extruded I WW

Status: Finished

Materials/Assemblies	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Polypropylene, granulate {RoW}| production | Conseq, S	0.91	kg	Undefined				

Processes	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Extrusion, plastic pipes {RoW}| production | Conseq, S	0.91	kg	Undefined				

Figure 10: Finished Manufacturing Process for WW Conveyance. PP Example.

As mentioned in other considerations, PB-1 and PVDF were not available on the Simapro libraries. Instead, external research allowed identifying similar studies that could be adapted to make a reasonable comparison to the data obtained from Simapro.

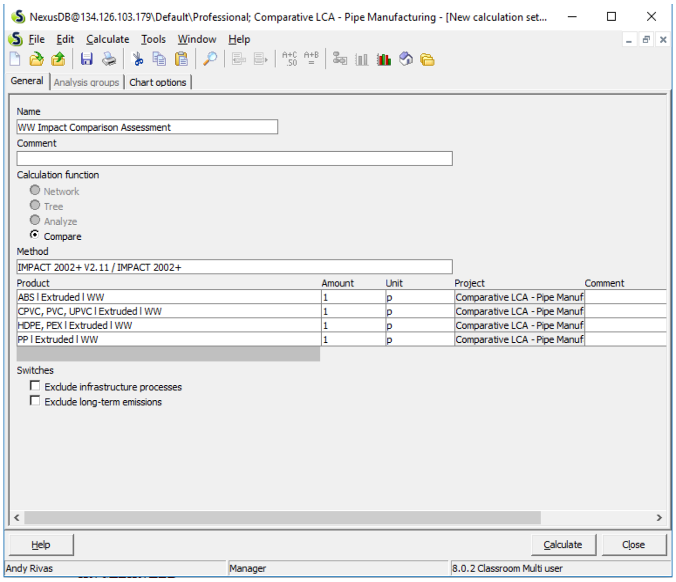
Two independent EPD’s were used as the foundation to analyze impacts associated with PB-1 and PVDF. Such studies are the following:

1. The first LCA was conducted by VITO, a sustainable development research organization, for the European Plastic Pipe and Fittings Association (TEPPFA). The 2015 study focused on a PB-1 pipe system used for hot and cold water distribution (Peeters, 2015). Although the LCA followed a cradle-to-grave approach, information was broken down so that impact associated with earlier stages of interest such as raw material extraction and processing could be easily obtained from their end results. The functional unit was defined as the energy and materials required to supply water to a 100 m^2 apartment. This functional unit required an amount of approximately 6.15 kg of PB-1 pipe (translated into 0.12298 kg/FU). Based on mass output calculations (Appendix 2) it was determined that 1.32 kg were needed to satisfy this LCA’s functional unit of transporting 100 in^3 of fluid. The ratio between these masses is approximately 6.14, therefore, all results associated with raw material extraction, processing and extruding were multiplied by 6.14. VITO conducted their study using the Ecoinvent libraries from Simapro, however, their LCA method used was not specified. Final impact categories were determined to be: abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion, and photochemical ozone creation.
2. The second EPD was created by Georg Fischer Piping Systems and is based on comprehensive reports written by VITO. The study focused on a PVDF system for ultra-pure water at a pharmaceutical in Switzerland (Georg Fischer Piping

Systems Ltd). The functional unit was defined as “The circling and distribution of purified water in a pharmaceutical plant in a loop over the length of 267.3 meters by a piping system.” The required amount of PVDF material was determined to be 321 kg by the researchers, which included both PVDF pipe and PVDF fittings. Unlike the PB-1 study, this EPD does not differentiate between pipes and fittings; however, it is specific in terms of how materials are grouped together. Their end results were multiplied by 0.00807 to meet the functional unit requirement of 2.59 kg of PVDF mass output (Appendix 2). GF Piping systems used the Ecoinvent libraries as well, but their LCA method was not specified. The impact categories presented included: Global warming, Ozone depletion, Acidification of soil and water, Eutrophication, Photo-chemical ozone creation. The analysis of PVDF included: raw material extraction, transport as defined by Ecoinvent to allow manufacturing, and extrusion/injection processes. This study can be found as an attachment.

After all processes were defined, the life cycle assessment methodology was determined. Initially to the plan was to use Impact 2002+ based on its feasible implementation of a mid-point damage-oriented approach. The method considers 14 different mid-point categories and link them to four impact categories: human health, ecosystem quality, climate change, and resources (Bengoa, 2012). After realizing that some data was not available, external research showed that other studies used EPD methods, which are available in Simapro as well. It was decided to use Impact 2002+ (as originally planned) for the wastewater products, and EPD 2008 for the drinking water study to be as consistent as possible with the data obtained through research.

Finally, all products within a category were selected and the compare tool was used to determine their impact relative to one another.



Name
WW Impact Comparison Assessment

Comment

Calculation function
○ Network
○ Tree
○ Analyze
● Compare

Method
IMPACT 2002+ V2.11 / IMPACT 2002+

Product	Amount	Unit	Project	Comment
ABS l Extruded l WW	1	p	Comparative LCA - Pipe Manuf	
CPVC, PVC, UPVC l Extruded l WW	1	p	Comparative LCA - Pipe Manuf	
HDPE, PEX l Extruded l WW	1	p	Comparative LCA - Pipe Manuf	
PP l Extruded l WW	1	p	Comparative LCA - Pipe Manuf	

Switches
☐ Exclude infrastructure processes
☐ Exclude long-term emissions

Andy Rivas | Manager | 8.0.2 Classroom Multi user

Figure 11: WW Products Impact Comparison Step on Simapro

Results and Justifications

The results obtained by running the compare tool described in the previous section are discussed for each of the two pipe groups. Uncertainty and limitation discussions play a critical role in how these results are interpreted, which finally address the main question of the study: what are the environmental impacts associated with each product of concern?

Wastewater Group

The first group included those materials typically used to build pipes designed for wastewater conveyance. The functional unit was defined as the volume of material needed to transport 100 in^3 of water at any given time, which was determined to average 60.4 in^3 for wastewater pipes (Appendix 1). The materials studied in this group were: ABS, PVC, UPVC, PP, HDPE, PEX. As addressed earlier, limitations on data availability led to grouping 1) PVC and UPVC and 2) HDPE and PEX. After running the compare tool, the following initial results could be determined:

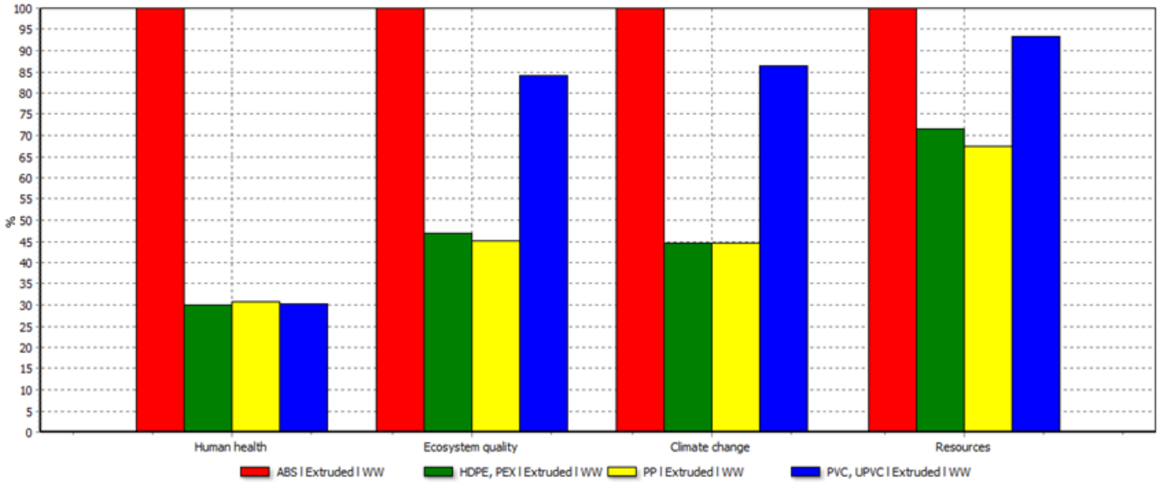
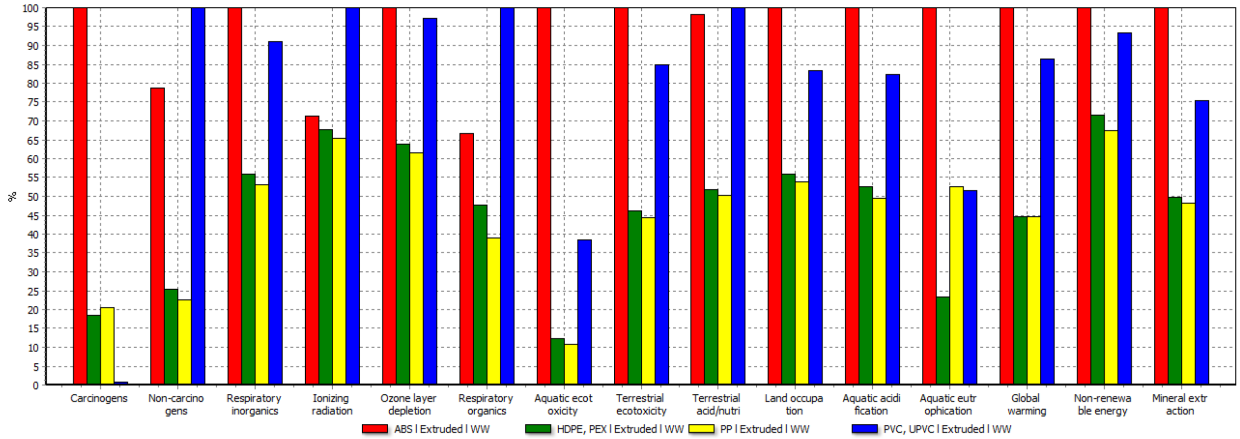


Figure 12: WW Damage Assessment

By looking at Figure 7 it can be determined that manufacturing ABS pipes has the largest impact through all categories, followed closely by PVC/UPVC (except for the human health category). The HDPE, PEX, and PP pipes seem to have relatively close impacts through all categories. These results were determined based on the Impact 2002+ method, which measures damage assessment by grouping 15 different midpoint categories. The characterization categories within the damage assessment allow taking a closer look at material performance and how it shaped results.



Comparing 1 p 'ABS l Extruded l WW', 1 p 'HDPE, PEX l Extruded l WW', 1 p 'PP l Extruded l WW' and 1 p 'PVC, UPVC l Extruded l WW';
Method: IMPACT 2002+ V2.11 / IMPACT 2002+ / Characterization

Figure 13: WW Characterization Categories

The Impact 2002+ groups mid-point categories into 4 damage categories the following way:

1. **Human health:** This category consists of human toxicity (carcinogens and non-carcinogens), respiratory effects (organics and inorganics), ionizing radiation, ozone layer depletion, and photochemical oxidation impact estimations. ABS seems to have a relatively similar impact on human health as PVC/UPVC except for the carcinogens emitted through its production, where ABS shows a

considerably higher impact relative to the rest of the materials. In Figure 7, it can be observed how PVC/UPVC has a considerably lower impact related to ABS, meaning the carcinogen midpoint played a critical role in this calculation. Similarly, HDPE/PEX and PP behave similarly through all mid-point categories used to measure impact on human health.

2. **Ecosystem quality:** This category is a result from the midpoint categories aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acid/nutrient, land occupation, aquatic acidification, and aquatic eutrophication. Through nearly all mid-point categories ABS showed to have a higher impact than the rest of the materials, followed not-so-closely by PVC/UPVC. Aside from aquatic eutrophication, HDPE/PEX and PP seemed to have similar impacts, whereas HDPE/PEX showed a considerably lower impact relative to the other materials.

3. **Climate change:** This category is only the result of a global warming midpoint category. ABS exhibited the highest impact through all materials, followed closely by PVC/UPVC. HDPE/PEX and PP demonstrated half the impact calculated for ABS.

4. **Resources:** The resources damage category is the result of estimated non-renewable energy use and mineral extraction. Although ABS performed higher in both midpoint categories, the difference was not as significant as it was through other categories. It could be observed how all materials showed similarly high resource requirements for processing.

From the results presented above, a best possible alternative cannot be selected. However, it could be stated that ABS exhibited a much higher impact relative to other materials through all damage categories studied. Therefore, ABS is the material most likely to have a negative impact on the environment. Selecting the best alternative, on the other hand, has a lot to do with impact category prioritization. For example, PVC/UPVC impacts were relatively close to ABS through most midpoint categories; however, it demonstrated a much lower carcinogen release compared to all other materials. For someone considering carcinogen release the most concerning category, this might be the best alternative regardless of its impact through other categories. It can be concluded that PP and HDPE/PEX pipes do not only behave similarly, but also had the lowest impact through all damage categories, making them the best selections for wastewater conveyance.

The results presented in this section are considered a consistent tool for decision making. However, some of the assumptions and limitations made could considerably influence the end-results. The grouping of PVC/UPVC and HDPE/PEX does not allow for evaluation of how much of an impact additives and cross-linking might have. Furthermore, molding processes are assumed to be the same for all materials, which may or may not be true in real practice. The most critical limitation found was the inability to access a step-view where impact at each stage of the process network could be quantified. This poses a limitation since determining where in the production process these impacts develop is crucial to pointing out concerning practices along the manufacturing process.

Drinking Water Group

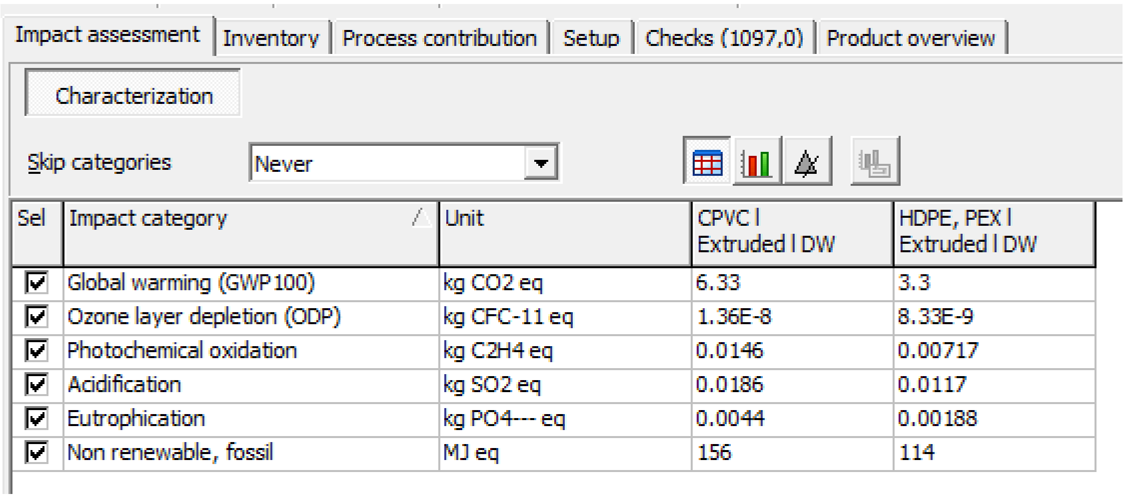
The second group consisted of pipe products used for drinking water supply. The functional unit for this group was defined as the volume of water needed to transport 100 in^3 of water at any given time, as for the previous group. The volume of material was determined to be 88.8 in^3 for drinking water pipes (Appendix 2). The materials studied within this group included: CPVC, PB, HDPE, PEX, PVDF. Limitations on data availability led to making assumptions on how these materials were evaluated, such as: 1) assuming CPVC is identical to PVC 2) assuming PEX is identical to HDPE and 3) seeking outside LCA research on PB and PVDF.

The LCA studies on PB and PVDF found from external sources shaped how these two materials were analyzed (more detail on these EPDs can be found both in the Methodology section). After taking into consideration appropriate factors (Appendices 3 and 4), the results from these studies are summarized in the following table:

Table 3: Summary of Results: PVDF and PB-1 EPD Research

IMPACT CATEGORY	**UNITS**	**PVDF**	**PB-1**
Global Warming	kg CO2 eq.	4.36	2.09
Ozone Depletion	kg CFC-11 eq.	6.6E-06	7.7E-08
Photochemical Ozone Creation	kg C2H4 eq.	1.2E-03	3.2E-04
Acidification of Soil and Water	kg SO2 eq.	3.2E-02	7.9E-03
Eutrophication	kg PO43- eq.	2.3E-03	8.8E-04

The LCA method used throughout these studies to obtain their results was not indicated. However, since these reports are known to be EPDs, the EPD 2008 method was used to evaluate CPVC, PEX, and HDPE, which had already been set up on Simapro (Appendix 2). After running the Simapro EPD comparison tool, the following results were obtained:



Skip categories: Never

Sel	Impact category	Unit	CPVC | Extruded | DW	HDPE, PEX | Extruded | DW
☑	Global warming (GWP100)	kg CO2 eq	6.33	3.3
☑	Ozone layer depletion (ODP)	kg CFC-11 eq	1.36E-8	8.33E-9
☑	Photochemical oxidation	kg C2H4 eq	0.0146	0.00717
☑	Acidification	kg SO2 eq	0.0186	0.0117
☑	Eutrophication	kg PO4--- eq	0.0044	0.00188
☑	Non renewable, fossil	MJ eq	156	114

Figure 14: EPD 2008 Method Results for CPVC, HDPE, and PEX

Impact outputs for each material were determined using the same units, which facilitated comparing all products within the drinking water group. For the non-renewable (fossil) and abiotic depletion categories, no results were available for all materials; therefore, it was neglected from the final discussions. The results were finally compared using a spreadsheet and relative impact percentage; where the highest value for a product was shown as 100% relative to the rest (Appendix 5). The following graphic summarizes the impact of all materials relative to each other:

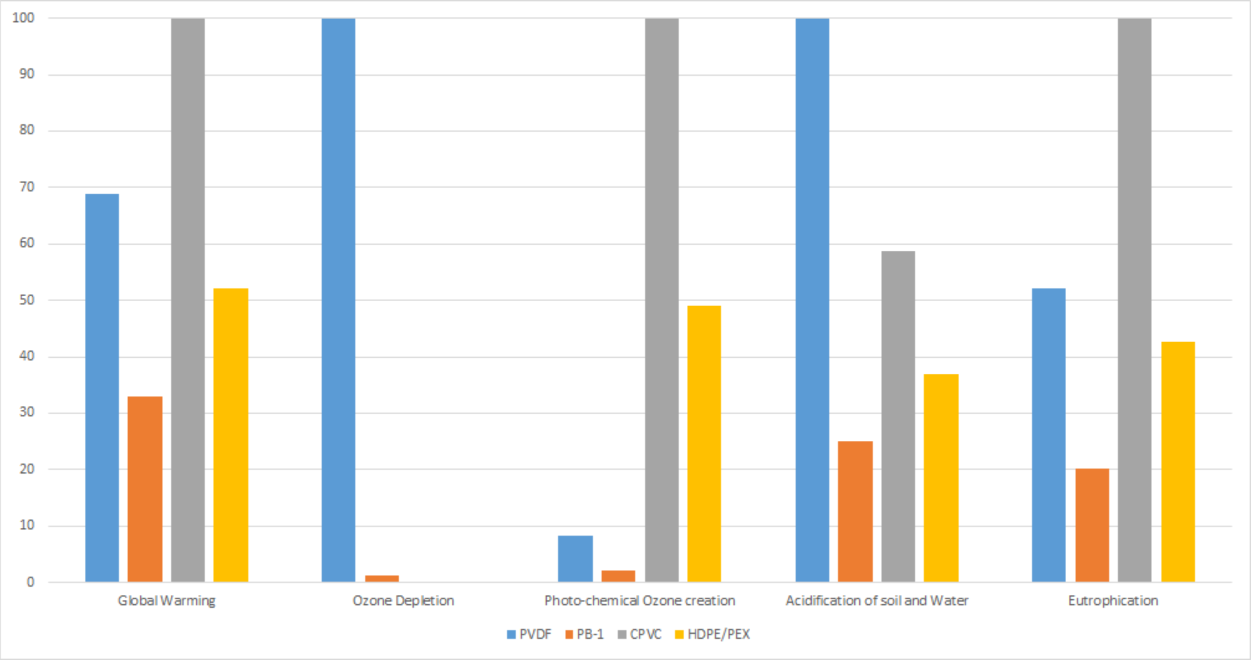


Figure 15: Summary of Impact Results DW Group

From Figure 10, CPVC and PVDF have the largest impacts compared to PB-1 and HDPE/PEX. Unlike Impact 2002+, EPD 2008 does not provide access to mid-point category measured; however, damage categories still provide a good foundation for discussion:

1. **Global Warming:** Global Warming Potential (GWP) is generally measured in terms of Greenhouse Gas (GHG) emissions leading to climate change. The burning of fossil fuels and the fact that these products are crude oil products play a critical role in GWP calculations. Impact was somewhat spread out through the different materials; CPVC seemed to have the largest impact compared to all of them, followed not-so-closely by PVDF. HPDPE/PEX and PB-1 showed a considerably lower GWP relative to other materials, with values of 52% and 33%, respectively.

2. **Ozone Depletion:** ozone layer depletion is associated with the chlorofluorocarbon release, which breaks down molecules absorbing UV radiation that could otherwise be potentially harmful to human health. Within this category, PVDF showed to have an extremely high impact compared to the rest of the materials (100% vs about 1% and below). This result seems reasonable considering not only that PVDF is derived from gaseous difluoroethylene, but it also requires plenty of solvents, acids, and bases to reach high-standard purity levels.

3. **Photochemical Ozone Creation:** although helpful to absorb UV radiation at higher levels in the atmosphere, ozone can have potential consequences at lower levels such as respiratory issues and crop damage. In this category CPVC demonstrated the highest impact, which is associated with the release of volatile organic compounds and nitrogen oxides. HDPE/PEX impact was measured at about 50% while PVDF and PB-1 exhibited relative impacts of 8% and below.

4. **Acidification of Soil and Water:** acidification of water is typically associated with carbon dioxide uptake while soil acidification results from increased levels of hydrogen and nitrogen. These could both be entitled to the impact of fossil fuels burned for energy processes at the raw material extraction, polymerization, and extrusion phases. PVDF had the greatest impact within the group, followed by CPVC, HDPE/PEX, and PB-1.

5. **Eutrophication:** this process results from high levels of nitrogen and phosphorous released to water bodies. The greatest impact was measured to be

that from CPVC, which is most likely associated with how GHG emissions and ozone creation take part in the hydrologic cycle. This disruption causes polluted rainwater to get into water bodies, eventually leading to low dissolved oxygen concentrations. PVDF, HDPE/PEX and PB-1 demonstrated a footprint of 50% and below relative to CPVC.

The impacts measured within this group showed a stronger differentiation relative to the wastewater group. Although material recommendation is typically defined by what categories we consider to be important, a fair conclusion could be reached this time. PB-1 exhibited a considerably lower impact through all categories except for ozone depletion (within 1% of the lowest impact determined), which was not found to be concerning. HDPE and PEX had a lower than average impact among the rest of the materials, making it a great second feasible choice. On the other hand, choosing what material might have the most impact on the environment cannot be concluded with certainty. In 3 out of 5 impact categories CPVC had the largest footprint, while PVDF had the greatest effect in the remaining 2 categories. The difference between CPVC and PVDF throughout the impact categories was not too substantial, which made it harder to choose one over the other.

The CPVC and HDPE/PEX results from the drinking water group are believed to be reliable for decision making purposes. Some of the limitations found throughout the Simapro setup led to making assumptions that might have influenced the results. Grouping of HDPE/PEX did not allow understanding to what degree cross-linking increase impact, while assuming CPVC to be just a PVC material neglects all the impacts associated with having a greater chlorine concentration. Furthermore, the selected extrusion method might not entirely represent the processes followed in real applications, but is a good representation of what products undergo upon polymerization.

The last and most influential piece of information came from external research. PB-1 and PVDF were evaluated based on studies conducted by outside groups. Although the EPDs are specific in terms of materials studied, functional unit determined, and software/databases used, some information was still required to obtain more accurate results. For example, for neither of the studies the LCA method was indicated. Furthermore, PVDF considers transportation processes from raw material extraction to processing where no detail is provided (other than it was obtained from the Ecoinvent libraries).

Conclusion

Water conveyance systems play a critical role in modern developed areas. Polymer pipes have been used for about a century, and their convenient physical properties have positioned them as the leading material in the piping industry. Having such influence in the market means that changes in current material selection and manufacturing could lead to significant changes in terms of the environmental footprint. This study decided to take into consideration nine commercially known materials used for water conveyance. Creating two groups, water and wastewater products, allowed for a better comparison based on a functional unit of conveying 100 in^3 of water at any given time.

To conduct this study, the LCA software tool Simapro 8.0.2 was used to define raw material extraction, polymerization, and molding processing methods required to obtain the final pipe products. Ecoinvent 3.01 databases compiled experimental and practical data from the pipe industry in countries around the world, to come up with average values that could be used to run a reliable comparative assessment. The LCA methods Impact 2002+ and EPD 2008 processed all the data inputs defined on Simapro to determine impact through predefined impact categories. External research was conducted as required since not all material data could be compiled using the Ecoinvent databases. Such research consisted of studies evaluating the impacts of PVDF and PB-1 systems as part of an Environmental Product Declaration (EPD).

Results and Limitations

While creating the product process networks on Simapro, data availability challenges were encountered, which led to making a few changes in the evaluation procedure. These challenges are all associated with raw materials not being available in the Ecoinvent database as needed for this study. These changes led to assuming UPVC and CPVC were identical to PVC, while PEX had the same properties as HDPE. Furthermore, PB-1 and PVDF analyses resulted from external research, for which assumptions made by these outside organizations were trusted using only a conversion factor to account for the differences in functional units. Other than that, the most influential limitation was not being able to access a step-wise impact assessment throughout the process network created in Simapro. The initial scope of this study was not only to see which materials had high environmental footprints relative to others, but where such impacts came from and to what degree.

Since product impact is measured through impact categories, it is not appropriate to simply point out what material is the best or worst alternative. Each material exhibited unique characteristics that led to different impacts through all categories. Footprint trends could be used to provide what was considered the most appropriate material selection. For the wastewater group, PP calculations demonstrated it had the lowest impact through nearly all impact categories, while for the potable water group, PB exhibited a much lower impact through almost all categories relative to other materials in its group.

Recommendations

Based on the results obtained from this study it is recommended that, when possible, customers should decide to buy PP pipes if they intend to use it for wastewater conveyance, or PB if pipes are to be used in drinking water systems. On the other hand, HDPE and PEX exhibited a reasonably low impact throughout all impact categories, making them a feasible second choice for both wastewater and drinking water applications. This recommendation is based merely on the results obtained by using the parameters defined throughout this study.

Based on the challenges encountered developing this study, expanding impact evaluation for these products is highly encouraged by using material-specific data for all products studied. Updated databases and appropriate molding methods would account for a more accurate process representation. Although the transportation processes associated with manufacturing these products was neglected, it is encouraged for future studies to consider it since it could have a significant influence on the end results. Similarly, some of the products used to make polymer pipes are known to be recyclable, which was neglected. Taking material reprocessing into account could potentially reduce measured natural resource depletion while reducing energy use. The role of the polymer industry is critical to compiling energy and material flows, for which their collaboration would allow for creating more accurate models. Furthermore, material categories could be expanded to account for products not as commercially popular since they might also be a feasible selection.

Appendices

Appendix 1: Functional Unit Calculations

FUNCTIONAL UNIT	
Volume of water (in^3)	**100**

FLUID TYPE	**Schedule**	**Nominal Pipe Size (in)**	**Outer diameter (in)**	**Wall thickness (in)**	**Radius (in)**	**Required length (in)**	**Material Volume (in^3)**
Water	80	1.00	1.315	0.179	0.479	139.1	**88.8**
Wastewater	80	1.50	1.900	0.200	0.750	56.6	**60.4**

Appendix 2: Final Mass Output Calculation

Material	**Density**	**Unit**
ABS	0.0379	lb/in^3
PP	0.033	lb/in3
HDPE	59.88	lbs/ft3
PEX	58.6	lbs/ft3
AVG PE	59.24	lbs/ft3
PB-1	0.91	g/cm^3
PVC	0.051	lb/in3
CPVC	0.055	lb/in3
UPVC	1.375	g/cm3
PVDF	1.78	g/cm3

Material	**Density (lb/in3)**
ABS	0.0379
PP	0.033
HDPE	0.0347
PEX	0.0339
AVG PE	0.0343
PB-1	0.0329
PVC	0.051
CPVC	0.055
UPVC	0.050
PVDF	0.0643

Potable Water Material	**Material Volume (in3)**	**Density (lb/in3)**	**Mass Output (lb)**	**Mass Output (kg)**	**Mass Input (due to Extrusion loss) (kg)**
AVG PVC-CPVC	88.8	0.053	4.71	2.13	**2.14**
AVG HDPE-PEX	88.8	0.0343	3.05	1.38	**1.39**
PB-1	88.8	0.0329	2.92	1.32	**1.33**
PVDF	88.8	0.0643	5.71	2.59	**2.60**

Waste Water Material	**Material Volume (in3)**	**Density (lb/in3)**	**Mass Output (lb)**	**Mass Output (kg)**	**Mass Input (due to Extrusion loss) (kg)**
AVG PVC-UPVC	60.4	0.050	3.04	1.38	**1.38**
AVG HDPE-PEX	60.4	0.0343	2.07	0.94	**0.94**
PP	60.4	0.033	1.99	0.90	**0.91**
ABS	60.4	0.0379	2.29	1.04	**1.04**

Appendix 3: EPD PB-1 Adjusted Final Results

Impact Category	**Abiotic depletion resources-elements**	**abiotic depletion (fossil fuels)**	**acidification for soil and water**	**Eutro-phication**	**Global Warming (GWP100a)**	**Ozone layer depletion (ODP)**	**Photo-chemical ozone creation**
Unit	kg Sb eq	MJ	Kg SO2 eq	kg PO4- eq	kg CO2 eq	kg CFC-11 eq	kg C2H4 eq
Product Stage							
Production raw materials for PB-1 pipes	4.43E-08	9.55	0.000941	8.92E-05	0.26	8.07E-09	0.0000523
Extrusion PB-1 pipes	1.12E-07	1.55	0.000353	5.46E-05	0.0799	4.53E-09	1.58E-09

Impact Category	**Abiotic depletion resources-elements**	**abiotic depletion (fossil fuels)**	**acidification for soil and water**	**Eutro-phication**	**Global Warming (GWP100a)**	**Ozone layer depletion (ODP)**	**Photo chemical ozone creation**
Unit	kg Sb eq	MJ	Kg SO2 eq	kg PO4-eq	kg CO2 eq	kg CFC-11 eq	kg C2H4 eq
Product Stage							
Production raw materials for PB-1 pipes	2.72E-07	5.86E+01	5.78E-03	5.48E-04	1.60E+00	4.95E-08	3.21E-04
Extrusion PB-1 pipes	6.88E-07	9.52E+00	2.17E-03	3.35E-04	4.91E-01	2.78E-08	9.70E-09
Total	**9.60E-07**	**6.82E+01**	**7.95E-03**	**8.83E-04**	**2.09E+00**	**7.74E-08**	**3.21E-04**

Appendix 4: EPD PVDF Adjusted Final Results

Impact Category	**Global Warming**	**Ozone Depletion**	**Acidification of soil and Water**	**Eutrophication**	**Photo-chemical Ozone creation**
Unit	kg CO2 eq	kg CFC-11 eq	kg SO2 eq	kg PO43- eq	kg C2H4 eq
PVDF 3 Stages	5400	0.0082	39.2	2.84	1.5

Impact Category	**Global Warming**	**Ozone Depletion**	**Acidification of soil and Water**	**Eutrophication**	**Photo-chemical Ozone creation**
Unit	kg CO2 eq	kg CFC-11 eq	kg SO2 eq	kg PO43- eq	kg C2H4 eq
PVDF 3 Stages	**4.3578**	**6.6E-06**	**0.031634**	**0.00229**	**0.0012105**

Appendix 5: EPD and Simapro Final Results, Drinking Water Group

IMPACT CATEGORY	**UNITS**	**MATERIALS**			
		PVDF	**PB-1**	**CPVC**	**HDPE/PEX**
Global Warming	kg CO2 eq	4.36	2.09	6.33	3.3
Ozone Depletion	kg CFC-11 eq	6.6E-06	7.7E-08	1.36E-08	8.33E-09
Photo-chemical Ozone creation	kg C2H4 eq	1.2E-03	3.2E-04	0.0146	0.00717
Acidification of soil and Water	kg SO2 eq	3.2E-02	7.9E-03	0.0186	0.0117
Eutrophication	kg PO43- eq	2.3E-03	8.8E-04	0.0044	0.00188

IMPACT CATEGORY	**UNITS**	**MATERIALS**			
		PVDF	**PB-1**	**CPVC**	**HDPE/PEX**
Global Warming	%	69	33	100	52
Ozone Depletion	%	100	1.2	0.2	0.1
Photo-chemical Ozone creation	%	8.3	2.2	100	49
Acidification of soil and Water	%	100	25	59	37
Eutrophication	%	52	20	100	43

Glossary

A

Amorphous: molecules in a polymer are oriented randomly and intertwined, in addition to having a glass-like, transparent appearance.

Acrylonitrile: highly poisonous organic compound generally used in plastic manufacturing. It is colorless, volatile, and has an onion-like odor (National Institutes of Health).

Acids: ionic compounds that can be broken apart when they are in water to form hydrogen ions. Acids are generally sour in taste and can burn human skin and other materials (University of Illinois Urbana-Champaign).

Abrasion: refers to the wearing-down, scratching or rubbing away of a material, generally undesirable and caused by exposure to physical weathering elements.

Antioxidant: molecules that reduce the rate of electron transfer between two reacting substances (Science Daily, 2016).

Active site: region of a substance acting as a catalyst where a chemical reaction takes place (Holmes, 2017).

B

Butadiene: colorless gaseous industrial chemical used as a monomer in the polymerization of certain polymers, generally rubber (National Institutes of Health).

C

Copolymer: type of polymer composed of two or more different monomer subunits used to create its chain (Reid, 2017).

Chlorination: process of adding chlorine to a material to eliminate infectious substances and prevent germs from reproducing (Centers for Disease Control and Prevention, 2015).

Corrosion: degradation of a material's properties due to its interaction with the environment (Shaw, 2006).

Catalyst: substance used to speed up a chemical reaction, but is not consumed by the reaction itself.

Computer Numerical Control (CNC): conversion of a computer-aided-design into numbers used as coordinates that control the movement of a manufacturing tool (Ryan, 2009).

Casting: small-scale production process that consists in filling a mold with a liquid synthetic resin, which then hardens to a desired shape.

Crystal Structure: unique arrangement of atoms within a structure that repeat periodically (Science Daily, 2016).

Coating: covering the surface of an object with a desire cross sectional area, generally using a molten substance.

Crystallinity: degree of structural order in which atoms or molecules are arranged in a polymer.

Curing: process by which liquid reactive polymers are irreversibly converted into insoluble solids (Babaevskii, 2010).

E

Exothermic: reaction or process that releases energy in the form of heat.

Emulsifying Agent: substance soluble in water that enables uniform dispersion of another substance of interest (Moffat, 2011).

F

Fused Deposition Modeling (FDM): manufacturing technology commonly used in 3D printing that consists in an additive principle of laying down material in layers to produce a part (Stratasys, 2017).

Fluorination: adding fluorine to a product under controlled conditions to enhance resistance of a material, generally plastic.

H

Hydrocarbons: organic compound made of only carbons and hydrogens.

Heterogeneous: mixture containing non-uniform composition.

I

Initiator: substance that can promote radical reactions, generally used in industrial processes such as polymer synthesis (March).

O

Oxidant: substance that gains electrons in a chemical redox reaction.

Organometallic: organic compounds containing a carbon-metal bond (Reusch, 2013).

P

Pigments: insoluble compounds intensely colored, used to paint other materials not as solutions, but as finely ground solid particles mixed with a liquid (Metych, 2016).

Polarity: distribution of electrical charge over two atoms bonded together (Atkins, 2017).

R

Radical: molecule that contains one or more unpaired electrons (Walling, 1998).

Resin: solid or semisolid insoluble substance obtained by plant exudation or a polymerization process.

S

Styrene: unsaturated hydrocarbon obtained as a petroleum by-product that can be easily polymerized.

Stabilizers: substance that inhibits a reaction between two or more chemicals.

Saturated Polymer: compound having a chain of carbon atoms linked by single bonds (Purdue University).

T

Thermoplastic: polymer that becomes homogenized liquid when heated and hard when cooled in a reversible process.

Thermoset: synthetic materials that strengthen during heating, but cannot be remolded after their initial heat forming.

Tensile Strength: the resistance of a material to fracturing under tension forces

U

Unsaturated: compound that has carbon double or triple bonds.

W

Welding: process of uniting softened surfaces with the aid of heat or solvents, allowing interdiffusion of polymer chains across an interface (TWI Global, 2017).

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