A holistic decision-making framework for selecting domestic piping materials

Juneseok Lee

ABSTRACT

A life cycle impact assessment (LCIA) was carried out for three types of materials commonly used in domestic plumbing systems, copper, cross-linked polyethylene (PEX), and chlorinated polyvinyl chloride (CPVC), to examine the efficiencies and tradeoffs involved in the material selection process. The LCIA results revealed that for all midpoint and damage impact categories, PEX systems have less of an impact on the environment than either copper or CPVC. The results from the LCIA approach were combined with economic, ergonomic, convenience, safety, and other relevant factors to produce a holistic decision model that can be used to optimize the material selection process. The model was applied to develop a formal preference elicitation methodology that revealed that health considerations (35%) have the greatest impact on consumer choice, followed by environmental impact (19%), taste and odor (13%), cost (11%), and corrosion resistance (10%). These findings will help policy experts and water utilities understand how homeowners make decisions and the factors they consider important when selecting alternative plumbing materials.

Key words | analytical hierarchical process (AHP), life cycle impact assessment (LCIA), plumbing materials

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INTRODUCTION

Our water infrastructure systems contribute significantly toward human well-being. In the United States alone, there are over 1 million miles of drinking water distribution systems, representing a tremendous infrastructure (Grigg 2013). This figure represents only the major systems that bring drinking water to individual houses; the minor systems that transport the water within privately owned property boundaries to feed home plumbing systems are not included in this estimate (Lee *et al.* 2009).

The need to measure and evaluate the long-term sustainability of the nation's water infrastructure has begun to be appreciated by economists, engineers, and environmental and social scientists (Racoviceanu *et al.* 2007). Life cycle assessment (LCA) and its more convenient variant life cycle impact assessment (LCIA) serve as important tools for calculating the environmental impact of a product or unit function over its entire life cycle, encompassing aspects such as extraction, production, use, and final disposal (ISO 2006; Frischknecht *et al.* 2007; Herstein *et al.* 2009). Previous researchers have applied LCA to the hydraulic design and material selection for major systems and to compare the environmental impacts of different pipe materials for water mains (Dennison *et al.* 1999; Herz & Lipkow 2002).

However, it has been estimated that in the USA, premise plumbing systems are at least five to 10 times the size of our public water mains systems (Loganathan & Lee 2005). Consequently, there is a pressing need to consider the environmental impacts associated with premise plumbing infrastructures. The objectives of this study are, therefore, to (i) perform an LCA on this overlooked component of the water infrastructure by examining the impact of the most commonly used piping materials to shed light on the efficiencies and tradeoffs involved in the material selection process, (ii) develop a holistic decision model that combines economic, ergonomic, reliability, and safety aspects with the LCA results to optimize material selection, and (iii) apply

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the model to create a survey to determine consumer priorities for the pipes utilized in minor systems.

This work develops the findings from previous studies (Lee *et al.* 2009, 2013) by analyzing the environmental impacts associated with the three materials most commonly used for premise plumbing in new homes: copper (which is used in 90% of new builds), cross-linked polyethylene (PEX) (7%), and chlorinated polyvinyl chloride (CPVC) (2%) (Marshutz 2001). The plumbing material framework utilized considers environmental impacts along with other important attributes such as corrosion resistance, convenience of installation, proven performance in the market, taste and odor of water, and cost (including labor and material), as shown in Figure 1. Details of LCA and the decision model are explained.

METHODS

Life cycle impact assessment

For this study, LCIA was utilized to reduce the enormous amount of time and effort involved in collecting comprehensive data for each individual environmental input and output. LCIA utilizes a compiled midpoint and damage category approach, minimizing data by combining all the different types of life cycle inventory (LCI) results into 14 midpoint categories and four damage categories. The 14 midpoint categories are: human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, aquatic acidification, aquatic eutrophication, terrestrial acidification/nitrification, land occupation, global warming potential, nonrenewable energy, and mineral extraction. The four damage categories are human health, ecosystem quality, climate change, and resources (Frischknecht *et al.* 2007).

The LCIA method avoids the need to analyze environmental inputs and outputs as entire sets of data for each phase of a functional unit's life by focusing solely on the LCI results, assigning a factor to single elementary flows in an inventory table. Different types of factors convert the LCI results as inventory components into characterized, normalized, or weighted midpoint categories, or into damage categories (Frischknecht *et al.* 2007). The environmental impact is expressed as a single score; the lower the point value, the lower the environmental impact. Environmental-impact scores for one product must differ from another by a factor of two or more to be clearly better or worse from an ecological point of view (Gerberit 2009).

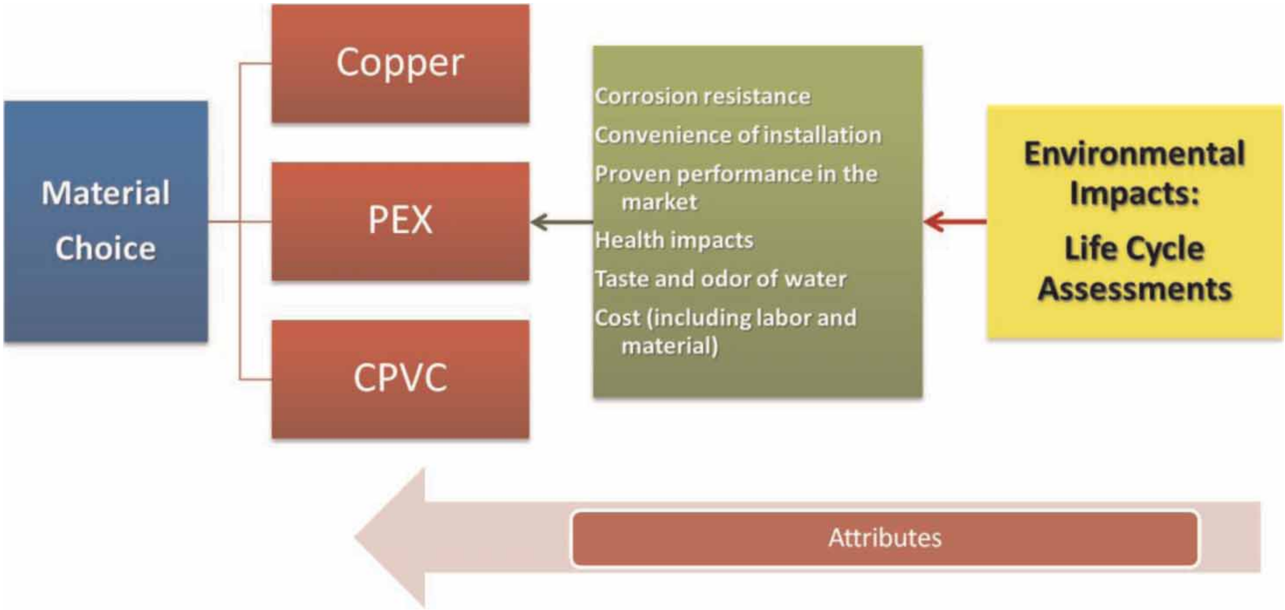

Figure 1 | Plumbing material choice framework.

For a more extensive discussion of the method, see Frischknecht *et al.* (2007).

Each of the three plumbing materials (copper, PEX, and CPVC) was analyzed from the production of raw materials to disposal or recycling, tracking all the associated environmental impacts in terms of inputs of resources and outputs of wastes and emissions. These three materials were compared for the amount of pipe needed in a typical single family residence, roughly 91.44 m of piping material, with a 100-year time period as the study's functional unit.

The inventory analysis examined the detailed procedures involved in the manufacture, use, and final disposal of the pipe, which constitute its life cycle. Each process required both inputs and outputs and here these were provided by Hewlett-Packard's Ecosystem Sustainability Assessment Tool (HP ESAT). These results represent the first attempt to analyze the environmental impacts associated with the production, use, and end of life stages for each of these plumbing materials. It is important to note, however, that the results can be case specific because of the uncertainty in the installation, maintenance, and operational use life stages and the distances traveled during the use and end of life stages. Hence, the installation, maintenance, and operational use life stages have been assumed to be independent of the pipe material and were therefore excluded from consideration by the boundary conditions. In similar LCA studies by Spirinckx *et al.* (2011a, b), the operational use and maintenance of a plumbing system was found to have no impact and the installation of a plumbing system was found to have only a relatively low impact, so the contribution of these phases would have little or no impact on the outcome and their contribution was deemed negligible.

Analytical hierarchical process

To develop a holistic decision framework, the analytical hierarchical process (AHP) was applied to the environmental impacts obtained from the LCIA results. The AHP determines preferences by pair-wise comparisons of attributes. Utilizing pair-wise preferences enables the decision maker to judge a pair of elements with respect to a single property without thinking about other properties or elements (Saaty 1980). In this survey, participants are asked to compare each paired attributes (total 21 comparisons) and materials (total three comparisons). Also, AHP includes a consistency check so respondents may be asked to repeat the procedure again, though some leeway is allowed to take into account the difficulty of giving precise preference judgments. More detailed coverage of the application of AHP to the choice of plumbing materials is provided in Lee *et al.* (2009).

The AHP surveys were administered to a group of Civil and Environmental Engineering (CEE) junior and senior students at San José State University during June 2014. Note that as almost none of the students own their homes, the results may not reflect the decisions of real homeowners. However, most of these students took water resources engineering and fluid mechanics courses as part of their required curriculum in CEE so they have reasonable technical backgrounds and familiarity with the drinking water infrastructure. Before completing the survey, the students were given a 30-minute presentation describing water distribution infrastructure problems from both the engineering and economics viewpoints to provide them with the necessary background for this survey. The pipe material and attributes information matrix used in the AHP survey is shown in Table 1.

RESULTS

LCIA

The LCIA results for the midpoint categories can be represented either as absolute units (kg_{eq} of a substance) or in relative units (% impact compared to a reference scenario) (Humbert *et al.* 2012). Figure 2 shows the LCIA results for the 14 midpoint categories using the predominant piping material, copper, as the reference scenario. The normalized LCIA results for the damage categories shown in Figure 3 represent their contribution to the overall damage in that category (Humbert *et al.* 2012).

Because of the degree of uncertainty associated with the possible distances traveled during the transportation phases, sensitivity analyses were deemed necessary for a range of specific scenarios. The distances traveled between the pipe production and use stages were varied from 500 to

Table 1 | Pipe material information matrix

Pipe material	Copper	PEX	CPVC
Corrosion resistance	Some risk of corrosion	Corrosion proof	Corrosion proof
Taste/odor	Compounds released may give a bitter or metallic taste or odor to the water	Compounds released may give a chemical or solvent taste or odor to the water	Compounds released may give a chemical or solvent taste or odor to the water
Health effects	Material meets EPA (Environmental Protection Agency) standards. There is a very small chance that compounds released into drinking water may cause vomiting, diarrhea, stomach cramps, and nausea	Material meets EPA standards. There is a very small chance that compounds released into drinking water may lead to microbial growth, potentially causing severe illness	Material meets EPA standards. There is a very small chance that compounds released into drinking water may lead to microbial growth, potentially causing severe illness
Convenience of installation	Penetration of walls and/or floors to replace existing system. Installation takes 7–9 days	Some sections of wall penetrated for installation. Installation takes 5–6 days. The pipes are flexible so easier to handle; but require additional fittings	Some sections of wall penetrated for installation. Installation takes 5–6 days. May suffer problems with cracking in freezing weather
Market history	More than 50 years in the market	About 20 years in the market	About 30 years in the market
Cost (labor + material)	$9,000–16,000, depending on the size of house	$6,500–13,000, depending on the size of house	$6,500–13,000, depending on the size of house
Environmental impacts	Copper and CPVC are similar	PEX is relatively smaller than copper and CPVC	Copper and CPVC are similar

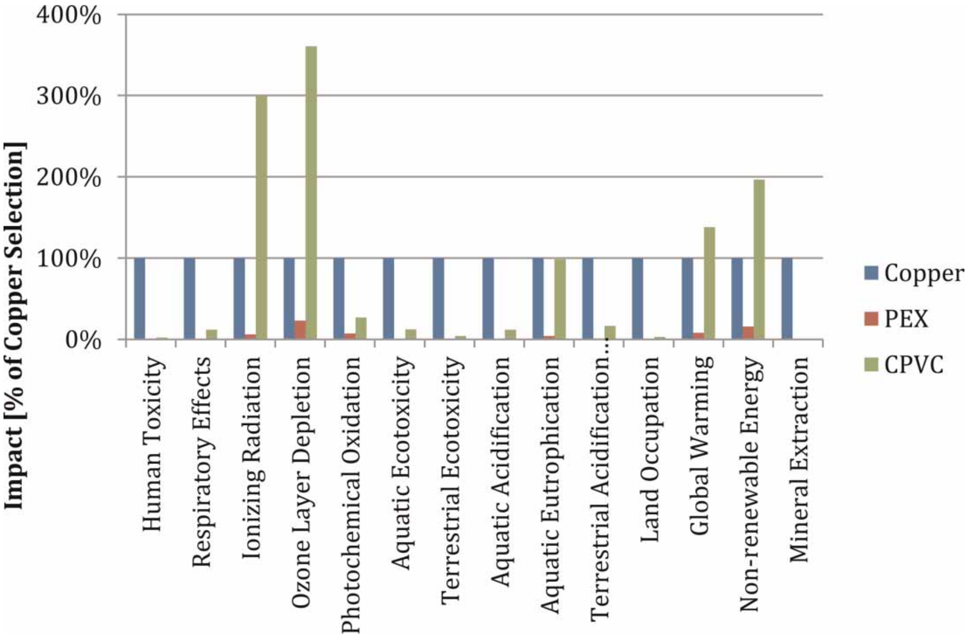

Figure 2 | Results for the 14 midpoint categories for PEX and CPVC compared to copper.

10,000 km, in 500 km increments, for each material to model realistic scenarios. The corresponding midpoint and damage categories were used to model the effects of differences in the distances traveled. For both copper and CPVC, distances traveled represented less than 2% of the life cycle impact in all midpoint and damage categories,

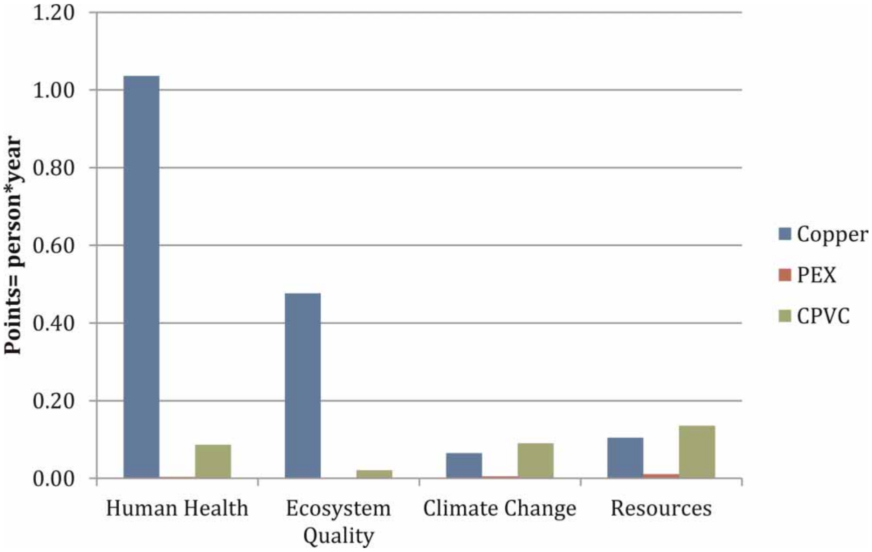

Figure 3 | Results for the normalized contributions of copper, PEX, and CPVC to the four damage categories.

but for PEX, there was a much greater life cycle impact: differences in distance traveled between 0 and 10,000 km altered midpoint categories by up to 20% and damage categories by up to 15% of the overall life cycle impact. This may be because PEX had a much lower impact in all categories, and as a result, the changes due to the varying distances traveled had a disproportionately larger impact. Comparing PEX to the reference scenario, copper, reduces the impact to less than 1% in all impact and damage categories.

These results suggest that the life cycle of a 91.44 m PEX pipe system has a markedly lower impact on all midpoint and damage categories than either copper or CPVC. CPVC systems appear to have a lower impact than copper in all midpoint categories except ionizing radiation, ozone layer depletion, global warming, and nonrenewable energy. The impact associated with CPVC and copper systems in the damage categories suggests that CPVC is better for human health and ecosystem quality, while copper is better for climate change and resource depletion. These findings support previous European research (Gerberit 2009) on supply pipes for buildings that compared a number of different pipe materials, including PEX and copper. Their conclusion was that copper pipes have an impact on the environment that is several magnitudes greater than that of PEX pipes.

AHP

A total of 26 students took the AHP survey, of which two surveys were incomplete so 24 surveys were analyzed. Of these, 13 passed the consistency ratio following Lee *et al.* (2009), which were deemed reliable. Their average attribute rankings are shown in Figure 4. Respondents ranked health effects (35 ± 9%) as their top priority, followed by environmental impacts (19 ± 9%), taste and odor of the water (13 ± 8%), cost (11 ± 9%), and corrosion resistance (10 ± 7%). These results indicate that health impacts dominate their preferences for plumbing materials. It is worth noting that environmental impacts were also quite

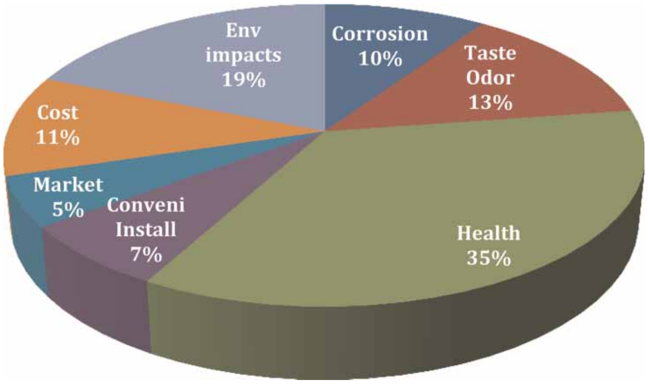

Figure 4 | Results for attributes.

influential in their decision. The final average ranking for the plumbing materials is shown in Figure 5; respondents ranked PEX (41 ± 11%) as their first options followed by CPVC (30 ± 10%) and copper (29 ± 16%). It is important to bear in mind that the context and type of information provided to the students inevitably had a significant impact on their final decision.

CONCLUSIONS

The findings of this study show that the environmental impact throughout the entire life cycle of a domestic premise plumbing system can be minimized through the appropriate selection of piping material. The results revealed that for all midpoint and damage impact categories, PEX systems have less of an impact on the environment than either copper or CPVC. The results from the LCIA approach were combined with economic, ergonomic, convenience, safety, and other relevant factors to produce a holistic decision model that can be used to optimize the material selection process.

A formal preference elicitation methodology was developed to assess various attributes of home plumbing systems. The resulting survey found that health considerations were deemed most important by consumers, followed by environmental impacts, taste and odor, cost, and corrosion resistance. Public perceptions of drinking water materials seem to be highly influenced by health effects, environmental impacts, and taste and odor impacts. Because the choice of an alternative plumbing material depends on the homeowner's perceptions, the context and type of information provided will play an important role in influencing preferences. These findings will help policy experts, water professionals, and water utilities understand how homeowners make decisions and the factors they consider important when selecting alternative plumbing materials.

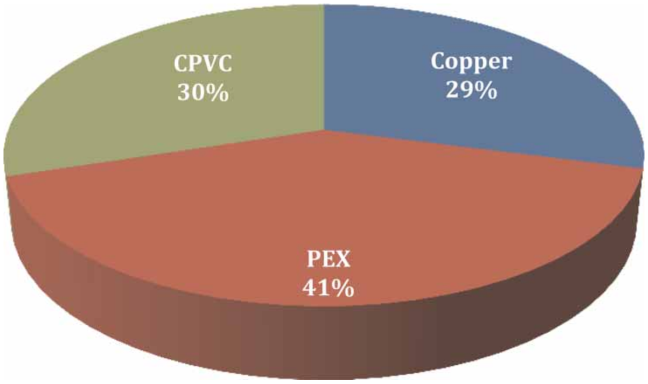

Figure 5 | Results for overall preferences.

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