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Life-cycle assessment of common water main materials in water distribution networks

L. M. Herstein and Y. R. Filion

ABSTRACT

This paper examines the economy-wide environmental impacts linked to the manufacturing of PVC and ductile iron (DI) pipes, steel tanks, and to the generation of electricity for pumping in water distribution network optimization. The non-dominated sorting genetic algorithm (NSGA-II) is used to generate Pareto-optimal solutions of the benchmark 'Anytown' network expansion problem. Selected Pareto-optimal solutions of the 'Anytown' network are evaluated with an economic input–output life-cycle assessment (EIO-LCA) and 14 environmental measures on air emissions, non-renewable energy use and environmental releases. The major findings suggest that DI and PVC pipe manufacturing and electricity generation activities (for pumping) have higher environmental impacts than steel tank manufacturing and construction activities in the 'Anytown' network. The EIO-LCA suggests that DI pipe manufacturing is linked to: (i) carbon monoxide emissions from truck transportation and wholesale trade and (ii) land and underground toxic releases from metal mining activities. PVC pipe manufacturing is linked to: (i) carbon monoxide emissions from truck transportation, (ii) toxic air releases from the plastics material and resin manufacturing sector, (iii) land and underground toxic releases from metal mining and resin manufacturing, and (iv) natural gas use for plastics material and resin manufacturing.

Key words | design, environmental sustainability, industrial supply chain, life-cycle analysis, material selection optimization, water distribution

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INTRODUCTION

The water industry is energy-intensive and resource-intensive. Building, retrofitting and operating a water network requires a significant amount of energy and materials and it also produces significant waste streams. For example, installing new pipes, tank and pump components to expand an existing water network involves a complicated industrial supply chain of sectors that carry out numerous material-extraction, material-processing, component-manufacturing and component-assembly activities. These industrial activities all require energy and some generate air emissions, greenhouse gas (GHG) emissions and solid waste streams. Moreover, producing electricity from fossil-fuel sources (e.g. coal and natural gas) to pump water also produces air emissions such as sulfur dioxide, nitrogen oxides, volatile organic compounds, particulate matter, etc. The replacement of old pipe, pump and tank components that cannot be recycled or re-used generates solid waste material that has to be disposed of in landfill.

There is a growing recognition that water utilities can account for the environmental impacts associated with the operation and management of their water systems. For example, in the United Kingdom the Water Services Regulation Authority (Ofwat) has mandated that water providers report their annual GHG emissions (Ofwat 2008). Ofwat has also recognized the need to account for the non-operational GHGs resulting from the production and manufacturing of water distribution network components such as pipes, tanks

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and pumps (Ofwat 2008). There is thus a need for a decision support system to assist water utilities in making crucial design and expansion decisions within emerging climate change agreements and policies that promote environmentally sustainable practices and procedures in the water industry. Further, a systems approach opens the prospect of tracking the economy-wide environmental impacts of building, retrofitting and operating water distribution networks.

As a first step towards developing a systems-level decision support system, there is a need to understand the industrial sectors and environmental impacts linked to water network retrofit, expansion and operation decisions. The objectives of the research reported in this paper are threefold: (1) to generate Pareto-optimal solutions of the benchmark 'Anytown' expansion problem with the non-dominated sorting genetic algorithm (NSGA-II); (2) to use economic input–output life-cycle assessment (EIO-LCA) to examine the economy-wide environmental impacts linked to the manufacturing of PVC and ductile iron (DI) pipes and steel tanks and to the generation of electricity for pumping in the Pareto-optimal solutions generated with the NSGA-II and (3) to use EIO-LCA to determine the main industrial sectors involved in the manufacturing of PVC and DI pipes and in the generation of electricity in the selected Pareto-optimal solutions.

The paper is organized as follows. First, recent research that has examined the sustainability of water distribution networks is reviewed. Next, the multi-objective approach and the non-dominated sorting genetic algorithm (NSGA-II) used to solve the 'Anytown' expansion problem are presented. The EIO-LCA used to evaluate the environmental inputs/outputs associated with Pareto-optimal solutions of the 'Anytown' network is discussed. (EIO-LCA is also used to identify participating sectors linked to the manufacturing of pipes and to the generation of electricity.) The basis for comparing the environmental inputs/outputs of different Pareto-optimal solutions is discussed and the preliminary 'Anytown' results are presented.

LITERATURE REVIEW

In the field of water distribution system design, attempts have been made to incorporate environmental concerns into the design process. Many of these attempts involve the application of Life Cycle Assessment (LCA), which quantitatively analyzes all environmental inputs and outputs resulting from a given design over the entire period of its life cycle including the extraction, manufacturing, use and disposal stages (UNEP 1996). The application of LCA to decision-making for water distribution systems has been explored in the literature. For example, Dennison *et al.* (1999) compared the environmental impact of alternative pipe materials using LCA while Lundi *et al.* (2004, 2005) applied LCA to compare alternatives for wastewater, stormwater and drinking water. The LCA method can also be combined with additional environmental impact measures, thereby providing a more thorough assessment of system impacts. For example, Jeppsson & Hellstrom (2002) combined LCA with Material Flow Analysis (MFA) to track individual mass flows of a given system from material extraction to disposal.

The EIO-LCA approach can be used in place of MFA to quantify national economy-wide environmental discharges linked to the fabrication of materials and components used in a water network. The EIO-LCA method traces monetary and material flows between industry sectors that directly or indirectly contribute to the production of a given item or service. As with LCA, this method has been applied to water network design to compare the environmental performance of network solutions. Filion *et al.* (2004) used EIO-LCA to quantify energy expenditure in the fabrication stage of a water distribution system to ultimately compare pipe replacement scenarios. Stokes & Horvath (2006) used EIO-LCA to compare impacts of water desalination, water recycling and water importation schemes to address water shortages in California.

Environmental impacts have been incorporated into water distribution system design and optimization. Dandy *et al.* (2006) were the first to use a single-objective optimization program to minimize the mass, embodied energy and GHG emissions associated with the manufacturing of pipes selected in a network design. More recently, Dandy *et al.* (2008) used the non-dominated sorting genetic algorithm (NSGA-II) to minimize the cost and embodied energy of unplasticised PVC (PVC-U) and modified PVC (PVC-M) pipes selected in a network design. Wu *et al.* (2008, 2009) formulated single-objective and multi-objective optimization approaches that considered the cost of GHG emissions in pipe manufacturing and electricity production for pumping in the design of a network. Their approach considered the impact of a range of discount rates and carbon prices on the capital and operating costs of Pareto-optimal solutions.

Since the work of Dandy *et al.* (2006), water network optimization has focused on incorporating multiple environmental criteria to guide the design of water distribution systems. Herstein *et al.* (2009*a*) developed an EIO-LCA-based Environmental Impact (EI) index that quantifies environmental impact measures such as unsustainable energy resource use, GHG emissions and toxic releases to air, water and land. Herstein *et al.* (2009*b*) combined their EI index with the multi-objective NSGA-II algorithm to optimize the 'Anytown' benchmark system by minimizing capital cost, operational energy use and the EI index.

Multi-objective optimization yields a set of optimal solutions, which must be analyzed by decision-makers before a final solution is chosen. This post-optimization decision-making process can be challenging due to the difficulty in quantifying social and environmental considerations, and weighing the competing interests of stakeholders. Although the EI index has been included in the WDS optimization in previous work (Herstein *et al.* 2009*b*), this paper seeks to demonstrate how an EIO-LCA can be used to evaluate a number of environmental measures in a post-optimization decision-making process. In this paper, an EIO-LCA is applied to better understand the environmental impacts of selected Pareto-optimal solutions as well as the industrial sectors that play a part in those impacts.

METHODS

The methodology outlined below seeks to optimize the expansion of an existing water distribution system in response to growing demand. In the context of this paper, 'expansion' activities include the selective addition of pipes in parallel to existing pipes, the addition of pipes where no pipes currently exist (these locations are predetermined), the selective cleaning and lining of existing pipes, and the addition of one tank at a known location. All of these activities are part of a 'one-time intervention' performed at the beginning of the system's design horizon. The goal of the optimization presented in this paper is to minimize the cost of expansion activities by determining: (1) the location and diameter of parallel pipes, (2) the diameter of new pipes, (3) the existing pipes to clean and line, and (4) the size of the new tank. In contrast, the 'rehabilitation' problem seeks to optimize the type, timing and location of rehabilitation activities (e.g. pipe replacement, pipe cleaning and lining, and maintenance) over the entire lifetime of the system.

Multi-objective optimization approach

The multi-objective optimization approach in this paper seeks to minimize two objectives. The first objective in Equation (1) is comprised of the cost of new and duplicate pipes, the cost of cleaning and lining existing pipes, and the cost of a new elevated tank with a predetermined location. The second objective in Equation (2) captures the annual energy use for pumping:

Minimize:

$$CC = \sum_{b=1}^{PP1} P(D_b, L_b) + \sum_{c=1}^{PP2} CL(D_c, L_c) + \sum_{d=1}^{TNK} TK(TD_d, EL_d) \quad (1)$$

$$NRGOF = \frac{\sum_{b=1}^{PMP} \sum_{t=1}^{T} E_{a,t}}{T} \quad (2)$$

where CC = capital cost, which includes the present value cost of new and duplicate pipes, pipe cleaning and lining, and a new tank ($); $PP1$ = number of new and duplicate pipes installed in a network; $P(D_b, L_b)$ = cost of pipe b with diameter D_b and length L_b; $PP2$ = number of existing pipes in a network that need to be cleaned and lined; $CL(D_c,L_c)$ = cost of cleaning and lining pipe c with diameter D_c and length L_c; TNK = number of tanks in a network; $TK(TD_d,EL_d)$ = cost of tank d with diameter TD_d and bottom elevation EL_d; $NRGOF$ = annual pumping energy use objective function (kWh/yr); PMP = number of pumps in a network; T = number of years in design period (yr); $E_{a,t}$ = electricity consumption of pump a in year t (kWh).

Capital cost and operational requirements for pumping were separated into two objectives since they are financed in different ways. Capital improvements in Canadian jurisdictions are often financed through one-time government grants and through budgetary reserves, while operational costs are funded with property tax and water and wastewater service revenues (AMO *et al.* 2001). Moreover, the second objective in (2) is expressed in terms of energy use rather than in terms of cost, mainly to minimize uncertainty from discounting. By minimizing annual pumping energy over the lifetime of the system, it follows that the cost of pumping will also be minimized.

The decision variables in the multi-objective approach are: (i) the diameter of new and duplicate pipes, (ii) cleaning and lining of existing pipes (yes/no) and (iii) the equivalent diameter of new tanks (with known tank location). The capital cost and energy use objective functions are constrained by the continuity, energy conservation, performance and design constraints below:

Subject to:

$$\sum Q_{in} - \sum Q_{out} = Q_k, \quad k = 1, 2, ..., NN \text{ nodes} \tag{3}$$

$$\sum h_f - \sum E_p = 0 \quad \text{for all loops} \tag{4}$$

$$x_{min} \leq x \leq x_{max} \tag{5}$$

$$y_{min} \leq y \leq y_{max}. \tag{6}$$

The constraint in Equation (3) ensures that continuity is satisfied at all network nodes, where NN = number of nodes; Q_{in} = pipe flow into node k; Q_{out} = pipe flow out of node k; and Q_k = external demand at node k. The constraint in Equation (4) ensures that energy is conserved around network loops, where h_f = headloss across a pipe and E_p = energy added to the water by a pump. A network solver external to the optimization program satisfies both the continuity and energy conservation constraints.

The performance constraints in Equation (5) place lower and upper bounds on pipe velocity (to prevent pipe wall scouring and deposition), on peak pressure head at nodes and on tank levels, where $\mathbf{x}$ = vector of parameters to be constrained (e.g. pipe velocity, pressure head, tank levels); $\mathbf{x}_{min}$ = vector of lower parameter bounds; and $\mathbf{x}_{max}$ = vector of upper parameter bounds.

The design constraints in Equation (6) are set by the size and type availability on some decisions variables (e.g. pipes and tank), where $\mathbf{y}$ = vector of decision variables subject to size and type availability; $\mathbf{y}_{min}$ = vector of lower bounds on size and type availability and $\mathbf{y}_{max}$ = vector of upper bounds on size and type availability. This ensures that the multi-objective optimization program chooses from a set of discrete pipe diameters and tank sizes.

Non-dominated sorting genetic algorithm (NSGA-II)

The non-dominated genetic algorithm-II (NSGA-II) (Deb *et al.* 2002) was used to explore the nonlinear, discrete and constrained search space of the 'Anytown' problem and solve the multi-objective framework presented above. The strengths of NSGA-II are its simple and effective constraint-handling technique, a rapid non-dominated sorting approach and the ability to preserve good solutions throughout the evolution process. Another key strength is that parameters do not need to be known *a priori* or 'tuned' prior to the optimization. A detailed description of NSGA-II is provided by Deb *et al.* (2002).

Economic input–output life-cycle analysis (EIO-LCA)

Economic input–output life-cycle assessment (EIO-LCA) was used to evaluate the environmental impact of Pareto-optimal 'Anytown' solutions found with the multi-objective approach and NSGA-II. Economic input–output modelling is a macroeconomic tool that tracks the monetary flows between industrial sectors of an economy that contribute goods, services and materials to a finished good such as a water main pipe, an elevated tank or a pump installed in a water network. For a specified amount (in dollars) of water main pipe, elevated tank or other components required in the design of a water network, economic input–output modelling is used to determine the economic output (in dollars) of the industrial sectors directly and indirectly involved in the production of that water main pipe, elevated tank or other water network component. Economic input–output models have been extended to estimate levels of environmental outputs per dollar of economic production from industrial sectors (Hendrickson *et al.* 1998) that contribute to the manufacturing and fabrication of water network components.

Environmental measures

In this paper, the on-line EIO-LCA model maintained by the Green Design Institute at Carnegie Mellon University (Carnegie 2009) was used to evaluate 14 environmental measures indicated in Table 1. The environmental measures are organized into three environmental categories of air emissions, non-renewable energy use and environmental releases. The air emission measures in Table 1 include air pollutants monitored by the United States Environmental Protection Agency (USEPA 2008). The measures on environmental releases to air, water and land in Table 1 are based on Toxic Release Inventory (TRI) data from the US Environmental Protection Agency (USEPA 2009). (The original grouping of categories and measures in Herstein *et al.* (2009*a*) has been changed in Table 1 to ensure a similar number of measures in each category and thus an approximately equal weighting of each category in the index.)

The environmental measures of selected Pareto-optimal solutions generated with NSGA-II are evaluated with the EIO-LCA. This evaluation is performed in three steps. First, the economic value of pipes and tanks and energy use for pumping is determined with cost data. Second, the economic value of pipes, tanks and energy use are entered into the EIO-LCA to calculate the mass of air emissions, the level of non-renewable energy and the mass of environmental release measures in Table 1. This step is indicated in Equation (7) for the mass of sulfur dioxide. Third, the mass of air emissions, the level of non-renewable energy and the mass of environmental releases are divided by the functional unit. In this paper, the functional unit is defined as the average day demand flow delivered to consumers (in megaliters per day, MLD) by the 'Anytown' network over the 20-year design period (so defined, the functional unit of water volume accounts for changes in population and per capita water consumption over the 20-year period). It is calculated by averaging the 1985 and 2005 average day demand flows reported in Walski *et al.* (1987). In Equation (7), the mass of sulfur dioxide is divided by the functional unit of average day demand:

$$\text{Environmental Measure} = \frac{\text{Mass of Sulfur Dioxide } (SO_2)}{\text{Average Day Demand}} \rightarrow \left(\frac{\text{kg } SO_2}{\text{MLD}}\right). \quad (7)$$

'ANYTOWN' CASE STUDY

The 'Anytown' benchmark system was used to preliminarily examine the supply-chain environmental inputs/outputs

Table 1 | Environmental categories and environmental measures

Environmental category	Environmental measure	Type	Units
Conventional air pollutants with known human health effects	Sulfur dioxide	Discharge	Metric tons (t)
	Carbon monoxide	Discharge	t
	Nitrogen oxides	Discharge	t
	Volatile organic compounds	Discharge	t
	Particulate matter <10 μm	Discharge	t
Non-renewable energy depletion	Coal	Consumption	Terajoules (TJ)
	Natural gas	Consumption	TJ
	LPG*, distillate fuel, residual fuel	Consumption	TJ
	Motor fuel, Jet fuel	Consumption	TJ
Releases to the environment	Global warming potential	Impact	t of CO_2 equivalents (t_{CO2})
	Total air releases	Discharge	Kilograms (kg)
	Water releases	Discharge	kg
	Land and underground releases	Discharge	kg
	POTW**, offsite transfers	Discharge	kg

* Liquefied petroleum gas.
** POTW: publicly owned treatment works.

linked to network design and expansion decisions in water networks. The purpose of this analysis was to transparently demonstrate the application of the EIO-LCA approach to this optimization problem. Therefore, the problem was simplified by limiting considered costs and system factors in order to avoid overcomplicating the analysis, thus facilitating further application to more detailed problems in the future. The original 'Anytown' pipe, pump and tank data are found in Walski *et al*. (1987). In this paper, the 'Anytown' problem was solved using the multi-objective NSGA-II optimization code developed by Deb *et al*. (2002) to minimize capital costs of new/duplicate pipes, cleaning and lining of existing pipes, and the addition of a single tank at a predetermined location in year one, and to minimize the energy use for pumping over the lifetime of the system. Rehabilitation activities over the lifetime of the system (e.g. continued maintenance, future pipe replacement, and future cleaning and lining) were not considered in the analysis. NSGA-II was used to generate a number of Pareto-optimal solutions with PVC and cement-mortar-lined ductile iron pipe materials. The supply-chain environmental inputs/outputs linked to selected Pareto-optimal solutions for the two pipe materials were evaluated by economic input–output life-cycle analysis. The methodology followed to perform this evaluation is explained in detail below.

Pipe costs and supply-chain impacts of pipe manufacturing

Pipe costs for PVC and cement-mortar-lined ductile iron pipe were determined from 2009 pricing from local pipe manufacturers in Table 2. Pipe pricing has been converted from Canadian to US dollars at an average 2009 exchange rate (Bank of Canada 2009). Environmental measures for pipe fabrication were evaluated with the EIO-LCA 1997 USA purchaser model (Carnegie 2009), which is based on 1997 purchaser dollars. The United States Bureau of Labor Statistics Producer Price Indexes (PPI) (USBLS 2009) were used to adjust the 2009 pipe costs (Table 2) to 1997 dollars. The 1997 unit costs for PVC and DI pipes were input into the 1997 USA purchaser price EIO-LCA model (Carnegie 2009) industry sectors 'Plastics pipe, fittings, and profile shapes' (sector #32612) and 'Fabricated pipe and pipe fitting manufacturing' (sector #332996), respectively, to evaluate the environmental measures in Table 1.

Table 2 | Nominal diameter, inner diameter, and unit cost for: (i) PVC pipe and (ii) cement-mortar-lined ductile iron pipe

	New PVC pipe		New DI pipe	
Nominal diameter (mm)	Inner diameter (mm)	Unit cost (US $/m)	Inner diameter (mm)	Unit cost (US $/m)
100	112.0	25.00	115.5	56.35
150	161.0	39.00	168.9	54.48
200	212.0	65.00	223.5	68.07
250	260.0	94.00	275.3	88.17
300	309.0	129.00	328.2	112.51
350	357.5	87.61	380.7	158.25
400	406.6	114.08	433.4	186.33
450	455.7	143.82	486.2	231.71
500	504.7	178.35	538.9	262.42
600	602.9	258.08	644.4	355.24
750	747.8	435.51	800.4	543.15

Pipe cleaning costs

Pipe cleaning costs were estimated using cleaning and cement-mortar-lining costs from Walski (1986) (Table 3). The 1984 cast iron pipe cleaning and cement-mortar-lining costs were adjusted to 2009 values with the Engineering News Record Construction Cost Index (ENR 2009). Cleaning and lining costs include the cost of labour, materials, equipment, and contractor overhead and profit, and exclude the cost of excavation, mobilization, temporary service or valve replacement (Walski 1986). The supply-chain impacts of cleaning and lining activities were not evaluated with EIO-LCA.

Tank location, tank costs and supply-chain impacts

In this case study, a new steel elevated tank was connected to node 140 of the 'Anytown' network. This location was chosen in advance of the optimization due to its selection in a number of 'Anytown' optimizations studies (Walski *et al*. 1987, Walters *et al*. 1999, Farmani *et al*. 2005). The size of the tank was included as a decision variable in the optimization problem. The selection of steel tank capacities and costs

Table 3 | Cleaning and lining costs of existing cast iron pipes

Nominal diameter (mm)	Cleaning and lining existing pipe Cost (US $/m)
100	N/A
150	N/A
200	54.10
250	58.82
300	66.26
350	N/A
400	N/A
450	N/A
500	N/A
600	N/A
750	78.56

N/A: Not applicable – existing pipes with these diameters are not present in the 'Anytown' system.

in Table 4 were based on a US steel water tower supplier. The PPI industry sector 'Other fabricated structural metal' (sector # 332312-5) was used to adjust the 2009 tank costs to 1997 tank costs. The 1997 tank cost was input into the 1997 EIO-LCA model (Carnegie 2009) in the EIO-LCA industry sector 'Water, sewer, and pipeline construction' (sector # 235910) to evaluate the environmental measures in Table 1.

Energy use in pumping

Daily pumping energy was determined by analyzing the system with EPANET2 (Rossman 2000). The 1985 and 2005 average daily nodal demands and the water use pattern presented in Walski *et al.* (1987) were used to model normal-day water use in the 'Anytown' network at the beginning and end of the 20-year period. The daily energy use was multiplied by 365 days/yr to obtain the annual energy use for the years 1985 and 2005. Annual pumping energy use, based on the 1985 normal-day water pattern, was applied over the first ten years of the system (1985–1995) and annual pumping energy use based on the 2005 normal-day water pattern was applied over the next 10 years of the system (1995–2005). The annual energy use for the 20-year design period was averaged over the two 10-year demand periods. Hazen–Williams 'C' factors of all three pipe materials were decreased over the two 10-year demand periods to account for pipe roughening and aging (see Table 5). Existing pipes that were cleaned and lined were assigned a 'C' factor of 125 (specified in Walski *et al.* (1987)) for the 20-year period.

Table 4 | Commercially-available steel tank volumes and costs

Capacity (m^3)	Capacity (US gal)	Cost (US $)
189	50 000	540 000
379	100 000	615 000
946	250 000	820 000
1893	500 000	1120 000
5678	1500 000	2770 000
7570	2000 000	3590 000

Supply-chain impacts of electricity generation for pumping

Environmental impacts of electricity production for pumping were determined by the 1997 US purchaser price EIO-LCA model (Carnegie 2009). The total 1997 electricity cost was calculated by multiplying the 1997 US energy price of $0.0685/kWh (USEIA 2009) by the total energy use over the 20-year period. The 1997 electricity cost was input into the 1997 USA purchaser price EIO-LCA model (Carnegie 2009) under the industry sector #2211 'Electric power generation, transmission, and distribution' to evaluate the environmental measures in Table 1.

Table 5 | Pipe Hazen–Williams 'C' factors in the first and second 10-year demand periods

Pipe material	'C' factor (first 10-year period)	'C' factor (second 10-year period)
New cement-mortar lined DI pipe	140[3]	130[1]
New PVC pipe	150[3]	135[2]
Ex. unlined pipes (60 years)	120	120
Ex. unlined pipes (100 years)	70	70
Cleaned and lined pipes	125	125

[1] 'C' factor of 130 for 20-year old cement-mortar-lined ductile iron pipes recommended by Sanks (2008).
[2] 'C' factor of 135 for 20-year old smooth plastic pipes recommended by Sanks (2008).
[3] New-pipe 'C' factors specified by PVC and DI pipe manufacturers.

Total cost, total supply-chain impacts and evaluation of environmental measures

The 2009 cost of selected Pareto-optimal solutions was calculated by summing the new and duplicate pipe cost, the cleaning and lining cost, and the tank cost. The environmental measure values in Table 1 for pipe manufacturing, tank manufacturing and construction, and electricity generation were summed together and divided by the average day water demand over the 20-year design period (functional unit).

Peak design demands and optimization constraints

The EPANET2 model (Rossman 2000) was used to analyze the system under two additional demand scenarios of maximum hourly demand (MHD) and maximum day demand (MDD) plus fire flow. The MHD peaking factor was set to 1.8 and the MDD peaking factor was set to 1.3 with a required fire flow of 32 L/s for all nodes aside from 158 L/s for node 90, 95 L/s for nodes 75, 115 and 55, and 63 L/s for nodes 120 and 160, as specified in the original 'Anytown' problem (Walski *et al.* 1987).

As mentioned above, pressure head, fluid velocity and tank level constraints were placed on the multi-objective optimization problem to ensure that these conditions were met by the solution found. These constraints were considered in addition to cost when evaluating solutions through a constrained tournament selection method implemented in NSGA-II and outlined by Deb *et al.* (2002). This method favours solutions that meet constraints over solutions that do not meet constraints. Minimum allowable pressure heads of 28 m H_2O and 14 m H_2O were set under maximum hour demand (MHD) and maximum day demand (MDD) plus fire flow, respectively (Walski *et al.* 1987). The maximum allowable pipe velocity was set to 3 m/s (Walski *et al.* 2001) under peak demand conditions to prevent pipe wall scouring. Minimum tank water levels were set to 3.05 m and maximum levels to 10.68 m (Walski *et al.* 1987).

RESULTS AND DISCUSSION

The Pareto-optimal solutions for the PVC and cement-mortar-lined ductile iron (DI) pipe materials are indicated in Figure 1. The fronts are convex to the origin, which indicates a trade-off between capital cost and annual pumping energy use. For capital costs ranging from $3.5–4.5 million, the Pareto front for DI pipes is located to the left of the Pareto front for PVC pipes. This offset is explained by the fact that non-dominated solutions for both DI and PVC pipe materials in Figure 1 have nominal pipe diameters in the range of 200–300 mm. For this range of pipe diameters, Table 2 indicates that the unit costs of DI and PVC pipe are similar, where the DI pipe has a lower unit cost than the PVC pipe for nominal diameters of 250 and 300 mm. Table 2 also indicates that, for nominal diameters between 200–300 mm, the inner diameter of the DI pipe is larger than that of the PVC pipe. Since DI pipes have a larger inner diameter than PVC pipes, they will generate smaller frictional headloss in the 'Anytown' system and thus reduce annual pumping energy requirements relative to the PVC pipe.

Figure 1 also indicates that, for capital costs ranging from $5.0–6.5 million, the Pareto fronts for DI and PVC pipe materials converge to a lower bound on annual pumping energy use of approximately 3.5 GWh/yr. This is explained by the observation that, for solutions with DI and PVC materials with high capital costs, large pipe diameters are chosen for new and duplicate pipes, which minimize dynamic losses in the 'Anytown' system. In these large-diameter solutions, annual pumping energy use is instead governed by the static lift requirement between the clearwell and the elevated tanks in the 'Anytown' system. Since the required static lift is independent of pipe sizing selection (for both DI

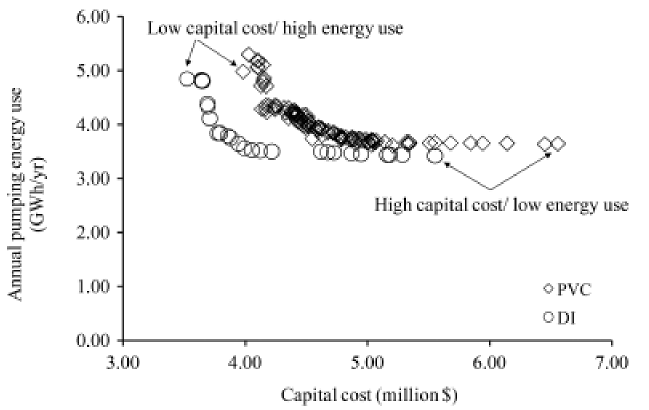

Figure 1 | Pareto-optimal fronts for capital cost versus annual pumping energy use for PVC and ductile iron (DI) pipe materials.

and PVC materials), a range of solutions with capital costs ranging between $5.0–6.5 million in Figure 1 will have approximately the same pumping energy use requirement of 3.5 GWh/yr.

The non-dominated solutions labeled 'Low capital cost/high energy use' and 'High capital cost/low energy use' for DI and PVC pipe materials in Figure 1 were selected to specifically examine and compare their environmental measures. Figures 2(a–d) indicate the 14 environmental measures for the 'Low capital cost/high energy use' (LC/HE) solutions and 'High capital cost/low energy use' (HC/LE) solutions with the DI pipe material. Different scales have been used on the *y* axis in Figures 2(a–d) for clarity of presentation and interpretation. The *x* axis in these figures indicates environmental measures and the *y* axis indicates the value of the environmental measure normalized by the functional unit of average daily demand over the 20-year 'Anytown' planning period. The contribution of pipe and tank manufacturing and electricity generation for pumping water is indicated in Figure 2(a–d). A number of observations are made here. First, it is clear that the pipe manufacturing and electricity generation make more significant contributions than tank manufacturing to all the environmental measures considered. Second, since the HC/LE solutions have high capital requirements (new and duplicate pipes with large diameters), the environmental impacts linked to pipe manufacturing are higher for these solutions than for the LC/HE solutions with generally lower capital requirements. Environmental impacts linked to electricity generation are similar in the HC/LE and LC/HE solutions.

Environmental measures were also examined for solutions with PVC pipe material. Figures 3(a–d) indicate the 14 environmental measures for the 'Low capital cost/high energy use' (LC/HE) solutions and 'High capital cost/low energy use' (HC/LE) solutions with PVC pipe material. Different scales have been used on the *y* axis in Figures 3(a–d) for clarity of presentation and interpretation. For PVC pipe material, pipe manufacturing and electricity generation make more significant contributions than tank manufacturing to all the environmental measures considered. The HC/LE solutions with high capital requirements have higher environmental impacts linked to pipe manufacturing than the LC/HE solutions with generally lower capital requirements. As in the case of the DI pipe material, the environmental impacts linked to electricity generation are similar in the HC/LE and LC/HE solutions.

It is noted here that no effort was made to compare the environmental impacts of solutions with DI and PVC pipe materials. Such a comparison can be misleading for two important reasons. First, the Pareto fronts indicated in Figure 1 and the environmental measures indicated in Figures 2 and 3 are sensitive to the physical characteristics of a network and to the pipe cost; both factors can vary across systems and across regions. Second, there is some uncertainty as to whether the Pareto fronts in Figure 1 include a comprehensive set of non-dominated solutions and whether the HC/LE and LC/HE solutions selected actually coincide with the 'true' extremes of these fronts. A fair comparison of the environmental impacts of DI and PVC pipe materials in a network requires that pipe material be included as a decision variable in the optimization problem.

Also examined in this paper were the supply-chain environmental impacts linked to the selection of DI and PVC pipe materials in the 'Anytown' network as well as the dominant industrial sectors responsible for those impacts. Figures 2(a–d) suggest that the dominant environmental impacts associated with pipe manufacturing in the DI pipe material solutions are carbon monoxide that originates from the truck transportation and wholesale trade sectors as well as land and underground toxic releases that originate from the copper, nickel, lead and zinc mining. Copper additives are used to increase the yield strength of ductile iron pipe while nickel and copper are used as anti-corrosion additives in ductile iron pipe. DI pipe manufacturing is also linked to significant greenhouse gas emissions (measured with the GWP measure in Figure 2(d)) that originate from electricity production by the power generation and supply sector to support pipe manufacturing processes. Figures 3(a–d) suggest that PVC pipe manufacturing activities are also responsible for a number of impacts that include: carbon monoxide emissions from the truck transportation sector, toxic air releases from the plastics material and resin manufacturing sector, land and underground toxic releases from copper, nickel, lead and zinc mining (land releases), and the plastics material and resin manufacturing sector (underground releases). PVC manufacturing activities are also linked to natural gas use for plastics material and resin manufacturing, and coal use and greenhouse gas emissions from the

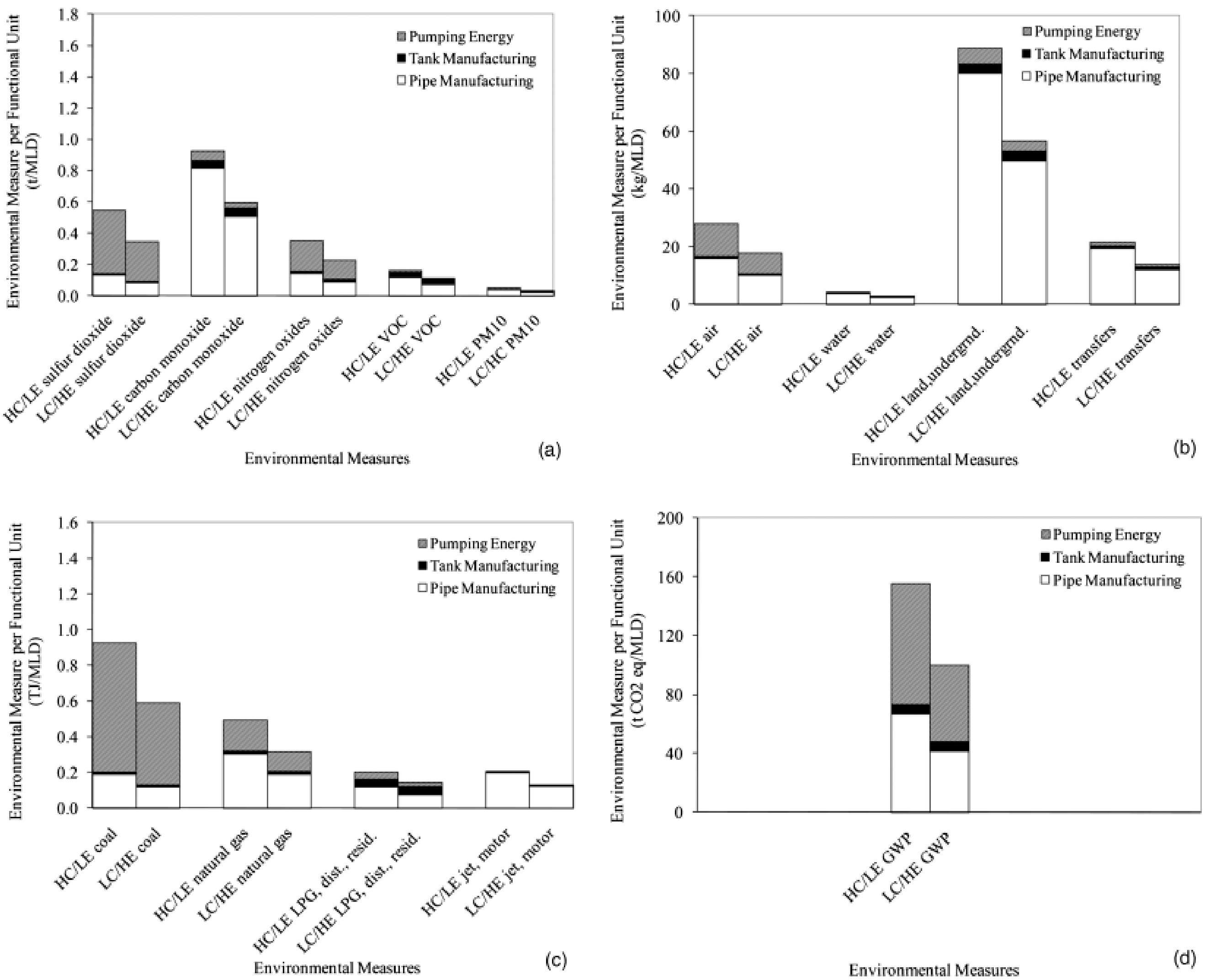

Figure 2 | Normalized environmental measures for the 'High cost/low energy' and 'Low cost/high energy' solutions with ductile iron (DI) pipe material.

power generation and supply sector to support manufacturing activities.

Figures 2 and 3 also suggest that the main environmental inputs and outputs of electricity generation (for pumping) water in the 'Anytown' solutions with both DI and PVC pipe materials are coal use, sulfur dioxide and greenhouse gas emissions. This result is not surprising given that electricity generation in the US relies heavily on fossil fuels (50% coal, 20% natural gas, 20% nuclear, 6% hydropower and 4% other) (USEIA 2010).

In the case of the 'Anytown' system, decision-makers may choose to use this information to decide which optimal solution would best suit their needs. For example, if a particular stakeholder is interested in two or three environmental measures, she may want to choose a particular solution that best minimizes these measures. The EI index has the potential for stakeholders to get a general overview of the overall environmental impact of a particular solution, as well as understand the causes of this impact and possible mitigation measures to make an informed decision regarding the best overall solution.

CONCLUSIONS

The paper sought to examine the economy-wide environmental impacts linked to the manufacturing of PVC and ductile iron (DI) pipes, steel tanks, and to the generation of

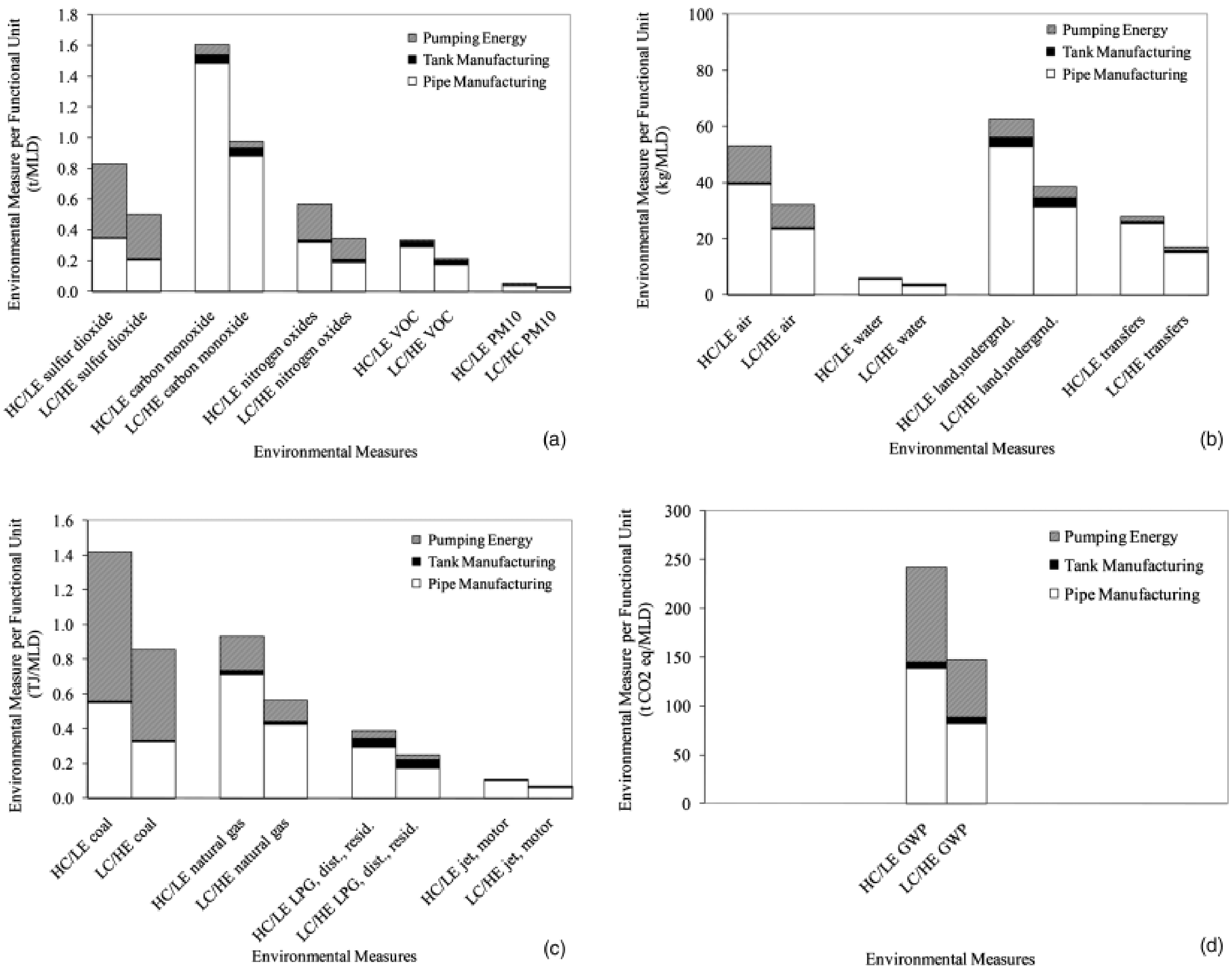

Figure 3 | Normalized environmental measures for the 'High cost/low energy' and 'Low cost/high energy' solutions with PVC pipe material.

electricity for pumping in water distribution network optimization. The non-dominated sorting genetic algorithm (NSGA-II) was used to generate Pareto-optimal solutions of the benchmark 'Anytown' network expansion problem. An economic input–output life-cycle analysis (EIO-LCA) and 14 measures on air emissions, non-renewable energy use and environmental releases were used to evaluate the environmental impacts of 'Anytown' solutions. The preliminary results suggest that DI and PVC pipe manufacturing and electricity generation activities (for pumping) have more significant environmental impact than steel tank manufacturing and construction activities in the 'Anytown' network. The EIO-LCA indicated that DI pipe manufacturing is linked to: (i) carbon monoxide emissions from truck transportation and wholesale trade and (ii) land and underground toxic releases from metal mining activities. In contrast, PVC pipe manufacturing is linked to: (i) carbon monoxide emissions from truck transportation, (ii) toxic air releases from the plastics material and resin manufacturing sector, (iii) land and underground toxic releases from metal mining and resin manufacturing, and (iv) natural gas use for plastics material and resin manufacturing. Electricity generation used for pumping water in the 'Anytown' network is heavily reliant on coal. Electricity generation was also directly linked to sulfur dioxide and greenhouse gas emissions. This is unsurprising given that the US relies heavily on fossil fuels (50% coal, 20% natural gas, 20% nuclear, 6% hydropower and 4% other) to generate electricity.

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