Environmental and Economic Analysis of a Water Network System Using LCA and LCC

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Water network synthesis has been used to conserve water resources and reduce costs. The objective of this study was to verify the higher eco-efficiency of a water network system (WNS), and to identify principal contributors to environmental burdens and economic costs using life cycle assessment (LCA) and life cycle costing (LCC). The WNS was compared to the conventional water system (CWS). LCA and LCC results showed that the total environmental burdens and life cycle cost of the WNS were lower than those of the CWS. The consumptions of industrial and ionized water were principal contributors to the environmental and economic burdens. The third principal contributor to the environmental burdens was electricity consumption, but that to the economic costs was piping cost. These principal contributors can be employed to obtain the simple and practical mathematical optimization models synthesizing the most environmentally friendly, economical, or sustainable WNSs. *AIChE J*, 53: 3253–3262, 2007
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Introduction

Because cleaner production is increasingly required in the context of sustainable development, much effort has been made to simultaneously reduce the environmental burdens and economic costs in processes, systems, utilities, products, and services. Water is an essential resource for washing and cooling, as well as being a product itself. Water consumption generates high environmental burdens and economic costs in water treatment, water supply, and wastewater treatment. In 1980, the first water network synthesis for a petroleum refinery plant was introduced to reduce the rates of freshwater consumption and wastewater generation.[1] Water network synthesis is optimizing a water supply system to maximize water reuse: water sources (e.g., wastewater, and/or treated wastewater) are used for water sinks (e.g., systems and processes), in case the properties of the water sources meet the requirement of the water sinks. The concept of water network synthesis is presented in Figure 1. Water network synthesis is in the context of the industrial ecosystem, where raw material consumption and waste generation are minimized because waste is used as raw material for another process.[2] Many water network synthesis technologies have been developed and practiced in industrial plants, to reduce the capital investment and operating costs in water systems. However, the improvement in the environmental and eco-

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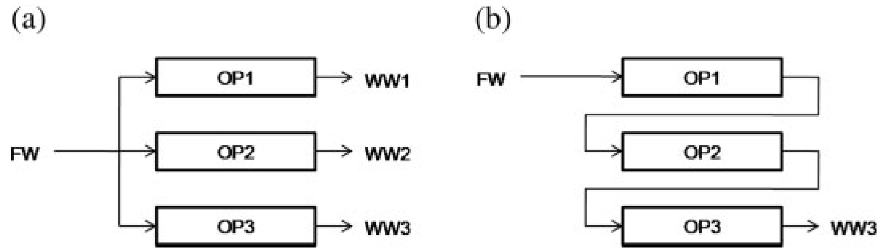

Figure 1. Concept of water network synthesis: (a) conventional water system (CWS); (b) water network system (WNS) (FW, fresh water; OP, water-using operation; WW, wastewater).

nomic performance of a water network system (WNS) during its life cycle has not been proved, even though it is the final goal of water network synthesis.

Most previous studies for water network synthesis have focused on solving mathematical formulations, such as nonlinear programming (NLP) and mixed integer nonlinear programming (MINLP), to find global optima.[1,3-7] Genetic algorithm was also applied to search global optima.[8] These approaches are necessary because of nonconvexities resulting from bilinear variables in the mass balances on contaminants.

Various objective functions have been intuitively formulated in previous studies because the environmental and economic analysis of WNSs has not been performed until now. Simple formulae for investment and operating costs were used to represent the total annual cost.[1] Most studies have minimized a single contributor, such as a total freshwater flowrate, the number of interconnections, or fixed costs.[6,8-11] Other studies have used the sum of the operating cost for freshwater and capital costs for pipes and wastewater treatment, the sum of the limited capital and operating costs,[7,12] or the sum of the costs of freshwater supply, water and wastewater treatment, pipes and sewers.[13] One multi-objective optimization studied to simultaneously minimize the total annualized cost and environmental impacts did not include piping costs.[14]

The intuitively formulated objective functions should not be used to synthesize the most environmentally friendly, economical, or sustainable WNSs because all principal contributors to environmental burdens and economic costs were not included in the objective functions. In other words, the WNSs generated from the intuitive objective functions were not the most environmentally friendly, economical or sustainable, even though the solutions of the mathematical optimization models for the WNSs were global optima. And it should be mentioned that the formulation of all contributors to environmental burdens and/or economic costs in the objective function is not preferable for obtaining simple and practical models: too complicated models can have the difficulty obtaining their solutions. Therefore, the environmental and economic analysis of a WNS is required to indentify the principal contributors to its environmental burdens and economic costs, which should be employed in formulating the objective function of the practical models synthesizing the most environmentally friendly, economical and sustainable WNSs.

Life cycle assessment (LCA) and life cycle costing (LCC) methods are useful tools to evaluate the environmental burdens and economic costs during the life cycle.[15-18] The eco-efficiency of systems and processes can be improved by reducing environmental burdens and economic costs while increasing profits and benefits. The concept of eco-efficiency has become more important for cleaner production and green engineering.[19] Each result of LCA and LCC can be combined to derive the eco-efficiency indicators used to compare the environmental and economic performance of alternatives.[20]

This study is the first attempt to analyze the environmental and economic performance of a WNS and provides fundamental and valuable information required to practically synthesize the most environmentally friendly, economical, and sustainable WNSs. The objective of this study is (1) to verify the higher eco-efficiency of the water network system than the conventional water system; (2) to identify principal contributors to environmental burdens and economic costs from water systems; and (3) to analyze the tradeoffs incurred from water network synthesis. To verify the improvement of its eco-efficiency, the environmental and economic performance of a WNS was compared with that of a CWS. A WNS was synthesized on the basis of a mathematical optimization model. The two water systems were designed to specify all the contributors. The CML2001 methodology used for the classification and characterization of environmental burdens was employed to evaluate their environmental performances in the LCA.[21] And LCC were employed to evaluate their economic performances.

Methods

Seven water-using operations in an iron and steel plant were employed as water sources and sinks for water network synthesis; these are used for steelmaking, continuous casting, and cold forming processes. The limiting process data for water network synthesis is presented in Table 1, showing the minimal operational conditions required for each water-using operation. The distance matrix for interconnections among the freshwater sources, operations, and local wastewater treatment plants was used to estimate the length of pipes, as provided in Table 2. Water is used for direct and indirect cooling, wet scrubbing, scale breaking, flume flushing, and cleaning. The capacities and concentrations of industrial and deionized water of freshwater sources are presented in Table 3.

Water network synthesis

A superstructure model was generalized to reflect real situations in the plant (Figure 2), which included all possible

Table 1. Limiting Process Data for Water Network Synthesis

Operation	Contaminant	$C^{max}_{c,opin}$, mg/L	$C^{max}_{c,opout}$, mg/L	M_{op}, kg/h	$F_{L,op}$, m^3/h	F^{min}_{opin}, m^3/h	F^{max}_{opin}, m^3/h
OP 1	CODcr	50	600	6.5	70.7	90	150
	SS	20	200	2.0			
	Cl^-	90	1100	12.9			
OP 2	CODcr	30	500	3.3	49.7	60	90
	SS	5	100	0.5			
	Cl^-	120	2300	16.4			
OP 3	CODcr	30	500	3.5	38.8	50	90
	SS	2	50	0.3			
	Cl^-	50	750	6.2			
OP 4	CODcr	20	250	2.3	36.6	50	90
	SS	3	50	0.4			
	Cl^-	20	300	3.0			
OP 5	CODcr	20	300	2.8	25.3	40	80
	SS	4	60	0.5			
	Cl^-	20	300	2.8			
OP 6	CODcr	23	400	3.2	8.3	20	70
	SS	5	80	0.6			
	Cl^-	10	200	1.5			
OP 7	CODcr	30	250	3.8	24.3	50	200
	SS	20	100	2.0			
	Cl^-	1	10	0.1			

interconnections between water sources and sinks. However, local recycling from the outlet to the inlet within an operation was not allowed, so as to prevent excessive costs of pumping with a high flowrate. This was because the small gap between the concentrations of inlet and outlet in the local recycling requires a high flowrate in the recycled line, to transfer the contaminant load of the operation into water.[5] Note that local recycling is useless if the operational conditions do not require a high flowrate. Direct connections between freshwater sources and local wastewater treatment plants were also prohibited, to avoid loss of freshwater. It was assumed that the mixers combined the many streams into a single stream and that the splitters divided a stream into all possible streams flowing to the water sinks.

On the basis of the limiting process data and the freshwater data, the original WNS was generated using the mathematical optimization model described in Appendix A. In this model, the total number of the variables is $(n^2 - n) + mn + 3n + 3cn$, and the total number of the equality constraints is $3n + 2cn$ (the number of the contaminants, freshwater sources, operations are c, m, and n, respectively). Therefore, the number of independent variable is equal to $(n^2 - n) + mn$. GAMS/MINOS[22] was used as an NLP solver to find solutions whose global optimality cannot be guaranteed by the chosen solution procedure. A linear programming (LP) model, generated by fixing the flowrates or concentrations in the mathematical optimization model, was used to determine initial points. However, it should be mentioned that even local solutions were useful for industrial applications if they achieved a significant reduction in the total freshwater cost. The wastewater streams were connected to the local wastewater treatment plants, reflecting the real circumstances in the plant. The original WNS resulting from the optimal solution was simplified by eliminating any inefficient interconnections with a flowrate of less than 4.0 m^3/h. This was done because interconnections with a low flowrate could reduce the environmental and economic performance of the WNS, and because the simplified WNS was practical for the implementation of a WNS. The simplified WNS was employed for the following water systems design, LCA and LCC analyses.

Water system design

The WNS and CWS were specifically designed to obtain their detailed data which was used for LCA and LCC. All contributors in the two water systems were specifically designed on the basis of practical implementation. To make impartial comparisons between the two water systems, the

Table 2. Distance Matrix

	FW1	FW2	OP1	OP2	OP3	OP4	OP5	OP6	OP7
OP1	2,250	280							
OP2	2,060	1,010	1,010						
OP3	4,960	4,930	4,980	4,980					
OP4	2,090	410	460	280	4,140				
OP5	920	1,010	1,030	140	4,120	650			
OP6	980	1,140	1,200	220	4,060	710	170		
OP7	4,550	4,580	4,660	4,390	380	4,280	3,900	3,850	
TP1			460	520		300	520	570	
TP2									300
TP3					410				

FW, freshwater; OP, water-using operation; TP, local wastewater treatment plant; Unit, meter.

Table 3. Capacities and Concentrations of Freshwater Sources

	Freshwater	$F_w^{\max}$, m^3/h	$C_{c,w}$, mg/L		
			CODcr	SS	Cl^-
FW 1	Industrial water	600	0	0	15
FW 2	Deionized water	250	0	0	0

CWS was revised using the same design criteria as those applied to the WNS.

Pipe diameter and head loss were calculated simultaneously with the flowrate and pipe length. Head loss was calculated using the Darcy-Weisbach equation.[23] The maximum head loss basis was set at 200 and 20 kPa for pumping and gravity flow, respectively. Carbon steel was selected for the pipe material. The Korean Standard, KS D 3507, was used to determine the specific characteristics of the pipe. The distances between the water sources and sinks were used as the pipe lengths of the interconnections. The specifications of the pumps and electric motors required for the transfer of freshwater and wastewater were determined in relation to the flowrate and water head requirements. The discharge pressure of a pump was determined by summing the head losses through the pipes and the water pressure required for the water-using operation. The water pressures required at the end of the pipe were assumed to be 250 and 100 kPa for water-using operations and local wastewater treatment plants, respectively. Pump pits were required for the storage of wastewater prior to it being pumped to the water-using operations for water reuse or to the local wastewater treatment plants. The hydraulic retention times of the pump pits were set at 30 min.

Life cycle assessment

LCA was performed to evaluate and compare the environmental burdens associated with the two water systems during their life cycle on the basis of their design results. The LCA procedure was performed in accordance with the ISO 14040 series of standards[24]: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation.

The goal of this LCA was to verify the higher environmental performance of the WNS. The scope definition included the system, function, functional unit, reference flow, system boundaries, allocation, data qualities, and assumptions. The system and its function were defined as a water system designed to supply the water-using operations with industrial and deionized waters, and to transfer wastewater to the local wastewater treatment plants. The functional unit was defined as a water system required for the seven water-using operations shown in Tables 1 and 2 during its life cycle (15 years). The reference flow was set to one unit of the water system. System boundaries included all the contributors in the water systems illustrated in Figures 3a,c. The allocation was not required in this LCA. The same data qualities were used for the comparative assessment, because most data were calculated on the basis of the same design criteria and assumptions. The service life of the two water systems was assumed to be 15 years with respect to the lifetime of the pipes and mechanical equipment.

LCI was performed to quantify all inputs and outputs associated with each water system throughout its construction, operations and maintenance (O&M), and disposal. The GaBi 4.0[21] and Ecoinvent v1.2[25] databases were used for the LCI: the databases show the quantity of all the materials and energy required to obtain the unit quantity of an item. Inventory in the construction stage included the manufacture of pipes, pumps and motors, construction of the pump pits, associated transportation, and piping works. Consumption of utilities (e.g., industrial and deionized water, electricity), and maintenance and repairs were included in the O&M stage. The disposal stage included the recycling of steel, iron, and copper, as well as the landfill of concrete.

LCIA was performed to evaluate the significance of potential environmental impacts on the basis of the results of the LCI. CML 2001 methodology was used for the classification and characterization, to evaluate the environmental burdens of the two water systems. The environmental impact categories consist of abiotic depletion, acidification, eutrophication, freshwater aquatic ecotoxicity, global warming, human toxicity, marine aquatic ecotoxicity, photochemical ozone creation, and terrestrial ecotoxicity.

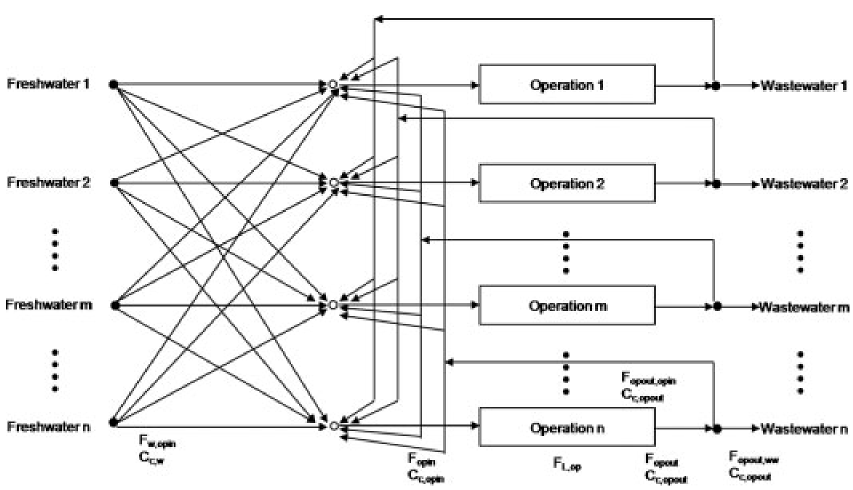

Figure 2. A generalized superstructure model used for the water network synthesis.

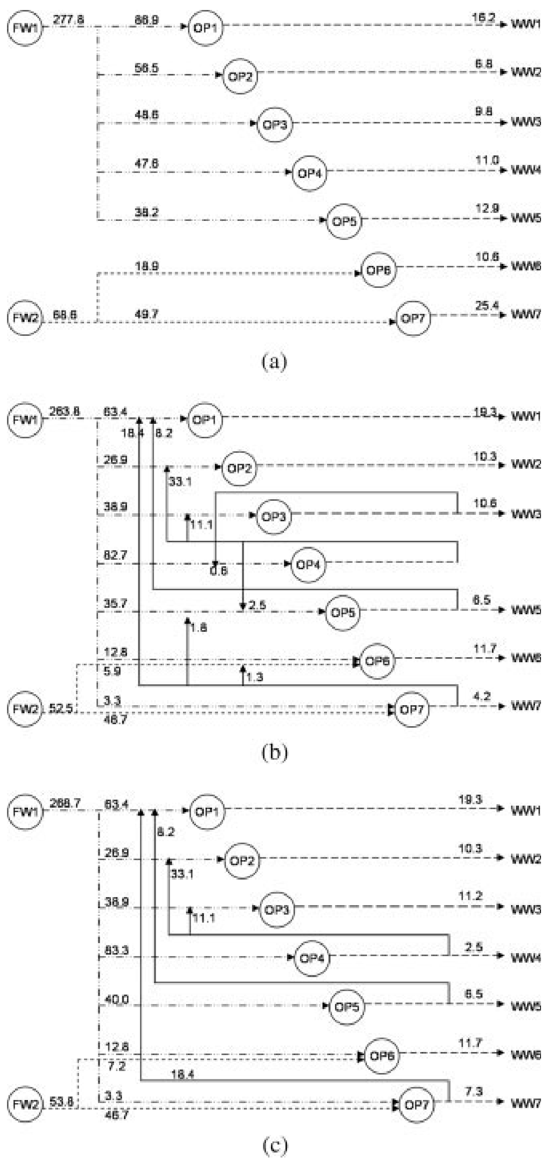

Figure 3. Comparison of the water systems: (a) conventional water system (CWS); (b) original water network system (WNS) generated from the optimal solution to the mathematical optimization model; (c) simplified WNS, modified by eliminating interconnections with a flowrate of less than 4 m^3/h (FW, freshwater; OP, water-using operation; WW, wastewater).

The life cycle interpretation was performed to comprehensively estimate the results of the preceding steps. The characterization results of the WNS were compared with those of the CWS, to examine the effect of the tradeoffs resulting from the water network synthesis on the variation of the environmental performance. Principal contributors to the environmental burdens were identified.

Life cycle costing

LCC analysis was employed to estimate the economic performance of the two water systems. The life cycle of the LCC was divided into four categories: (1) design and supervision, (2) construction, (3) O&M, and (4) disposal. The design and supervision stage consisted of the basic and detailed designs, as well as supervision. The cost of the construction stage was divided into the costs for piping, equipment (pump and motor), pump pits, construction expenses, and the contractor's overhead and profits. O&M cost included the operating cost of industrial and deionized water, electricity, and maintenance and repairs. The cost of the disposal stage was divided into the costs for recycling, landfill and construction expenses, and the contractor's overhead and profits. The cost estimation was performed using databases consisting of price and cost information.[26,27] The service life for the LCC was set at 15 years, as in the LCA.

After future costs were discounted to present values with respect to the time value of money, the present values were summed to obtain the life cycle cost for each water system. Because the O&M cost recurred annually and the disposal cost was incurred at the end of the service life, they had to be converted to present values, to be equally estimated and compared with an initial capital investment cost.[18,28] The present value was estimated using the following equation:

$$PV = P(1+e)^t/(1+i)^t \tag{1}$$

where PV = present value; P = future value; e = escalation rate; i = discount rate; t = time.

To discount future costs, the discount rate was set at 5.7% in relation to the yields of treasury bonds (5-years) over the last 10 years in South Korea,[29] and the escalation rate was assumed to be 3.0% targeted by the Bank of Korea for the period between 2004 and 2006.[30] The life cycle costs of the two water systems were compared to examine the effect of the tradeoffs resulting from the water network synthesis on the variation of the economic performance. Principal contributors to the economic costs were identified.

Table 4. Summary of the Design Results for the Conventional Water System (CWS) and Water Network System (WNS)

Life Cycle Stage	Contributor		Unit	CWS	WNS
Construction and Disposal	Pipe	Length	m	21,140	36,780
		Weight	kg	507,648	630,648
	Pump	Weight	kg	642	2,333
	Motor	Weight	kg	726	948
	Pump pit	Volume	m^3	46	70
Operations and Maintenance (O&M)	Industrial water	Flowrate	m^3/h	277.8	268.7
	Deionized water	Flowrate	m^3/h	68.6	53.8
	Total electricity consumption during life cycle (in thousands)	Energy	kWh	10,762	11,602

Table 5. Results of the Life Cycle Impact Assessment for the Conventional Water System (CWS) and Water Network System (WNS) in the Life Cycle Stage

			ADP	AP	EP	FAETP	GWP	HTP	MAETP	POCP	TETP
Construction (A)	Pipe	CWS	1.1E+03	5.7E+02	1.2E+02	7.4E+04	1.4E+05	4.7E+05	8.6E+07	1.6E+02	1.1E+03
		WNS	1.4E+03	7.1E+02	1.5E+02	9.1E+04	1.7E+05	5.8E+05	1.1E+08	2.0E+02	1.4E+03
	Pump	CWS	3.2E+00	9.9E-01	1.2E-01	2.4E+00	5.2E+02	3.2E+02	2.9E+04	1.9E-01	2.1E-01
		WNS	5.0E+00	1.5E+00	1.8E-01	3.7E+00	8.1E+02	4.9E+02	4.5E+04	3.0E-01	3.3E-01
	Motor	CWS	5.6E+00	2.1E+01	2.5E-01	3.4E+01	8.4E+02	9.0E+02	2.7E+05	1.3E+00	3.4E+00
		WNS	7.3E+00	2.7E+01	3.3E-01	4.5E+01	1.1E+03	1.2E+03	3.6E+05	1.7E+00	4.4E+00
	Pump pit	CWS	1.1E+01	1.3E+01	1.3E+01	1.2E+02	5.1E+03	5.4E+02	1.7E+05	1.4E+00	1.0E+01
		WNS	1.8E+01	2.1E+01	2.2E+01	1.9E+02	8.4E+03	8.8E+02	2.7E+05	2.3E+00	1.7E+01
	Sub-total	CWS	1.1E+03	6.1E+02	1.3E+02	7.4E+04	1.4E+05	4.7E+05	8.7E+07	1.6E+02	1.1E+03
		WNS	1.4E+03	7.6E+02	1.7E+02	9.2E+04	1.8E+05	5.9E+05	1.1E+08	2.0E+02	1.4E+03
O&M (B)	Industrial water	CWS	7.2E+04	7.1E+04	1.2E+04	2.5E+06	1.3E+07	1.1E+07	7.1E+09	7.3E+03	1.1E+05
		WNS	7.0E+04	6.9E+04	1.1E+04	2.4E+06	1.3E+07	1.0E+07	6.9E+09	7.1E+03	1.0E+05
	Deionized water	CWS	4.4E+04	3.8E+04	5.6E+03	1.3E+06	9.5E+06	5.7E+06	4.1E+09	3.4E+03	1.2E+05
		WNS	3.4E+04	3.0E+04	4.4E+03	9.9E+05	7.4E+06	4.4E+06	3.2E+09	2.7E+03	9.7E+04
	Electricity	CWS	4.6E+04	1.2E+04	1.3E+03	6.5E+05	7.9E+06	2.6E+06	3.5E+09	1.2E+03	1.1E+05
		WNS	5.0E+04	1.3E+04	1.4E+03	7.0E+05	8.5E+06	2.8E+06	3.8E+09	1.3E+03	1.2E+05
	Maintenance & repairs	CWS	5.1E+02	2.7E+02	6.1E+01	3.3E+04	6.5E+04	2.1E+05	3.9E+07	7.2E+01	5.1E+02
		WNS	6.4E+02	3.4E+02	7.8E+01	4.1E+04	8.2E+04	2.6E+05	4.9E+07	9.0E+01	6.3E+02
	Sub-total	CWS	1.6E+05	1.2E+05	1.9E+04	4.4E+06	3.1E+07	1.9E+07	1.5E+10	1.2E+04	3.4E+05
		WNS	1.5E+05	1.1E+05	1.7E+04	4.1E+06	2.9E+07	1.8E+07	1.4E+10	1.1E+04	3.2E+05
Disposal (C)	Steel and iron recycling	CWS	3.7E+03	1.7E+03	1.4E+02	6.0E+02	3.9E+05	2.4E+05	1.1E+08	2.6E+02	1.2E+02
		WNS	6.9E+03	3.1E+03	2.5E+02	1.1E+03	7.3E+05	4.5E+05	2.0E+08	4.8E+02	2.3E+02
	Copper recycling	CWS	1.4E+00	1.9E+01	8.3E-02	8.4E+04	1.8E+02	3.3E+02	1.7E+07	9.9E-01	1.1E+00
		WNS	3.4E+00	4.3E+01	1.9E-01	2.0E+05	4.1E+02	7.6E+02	4.0E+07	2.3E+00	2.6E+00
	Landfill	CWS	4.4E+00	5.6E+00	3.1E+00	1.6E+01	3.9E+02	1.6E+02	3.8E+04	8.0E-01	1.2E+00
		WNS	1.5E+01	1.9E+01	1.0E+01	5.2E+01	1.3E+03	5.2E+02	1.3E+05	2.7E+00	4.0E+00
	Sub-total	CWS	3.7E+03	1.7E+03	1.4E+02	8.5E+04	4.0E+05	2.4E+05	1.3E+08	2.6E+02	1.3E+02
		WNS	6.9E+03	3.2E+03	2.6E+02	2.0E+05	7.4E+05	4.5E+05	2.4E+08	4.8E+02	2.4E+02
Total (A + B + C)		CWS	1.7E+05	1.2E+05	1.9E+04	4.6E+06	3.1E+07	2.0E+07	1.5E+10	1.2E+04	3.4E+05
		WNS	1.6E+05	1.2E+05	1.8E+04	4.4E+06	3.0E+07	1.9E+07	1.4E+10	1.2E+04	3.2E+05

CML 2001 Methodology was employed for the classification and characterization.

ADP, abiotic depletion potential [kg Sb-equivalents]; AP, acidification potential [kg SO_2-equivalents]; EP, eutrophication potential [kg Phosphate-equivalents]; FAETP, freshwater aquatic ecotoxicity potential [kg DCB-equivalents]; GWP, global warming potential (100 years) [kg CO_2-equivalents]; HTP, human toxicity potential [kg DCB-equivalents]; MAETP, marine aquatic ecotoxicity potential [kg DCB-equivalents]; POCP, photochemical ozone creation potential [kg Ethene-equivalents]; TETP, terrestrial ecotoxicity potential [kg DCB-equivalents]; DCB, 1,4-dichlorobenzene.

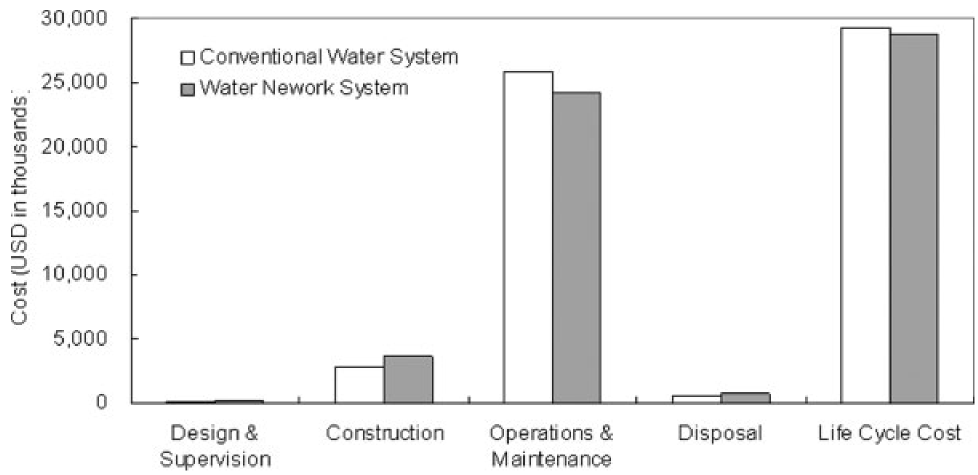

Figure 4. The results of the cost estimation in each life cycle stage and the life cycle costs.

Future costs were discounted to present values.

Results and Discussion

The original WNS was generated from the optimal solution to the mathematical optimization model (Figure 3b), and was first compared to the CWS (Figure 3a). The water network synthesis reduced total freshwater consumption rate from 346.4 to 316.3 m^3/h (8.7%), which showed its contribution to the conservation of water resources and to the reduction of freshwater costs. The decrease in the flowrate of deionized water was greater than that of industrial water. The flowrate of deionized water was decreased from 68.6 to 52.5 m^3/h (23.5%), while that of the industrial water was diminished from 277.8 to 263.8 m^3/h (5.0%). This difference was due to the objective function of the mathematical optimization model which drove the reduction of deionized water cost rather than that of industrial water cost, because the unit cost of deionized water is higher than that of industrial water. The flowrate of wastewater was also reduced from 92.7 to 62.6 m^3/h (32.5%). This reduction would improve the removal efficiencies and lower the operating cost in the existing local wastewater treatment plants because of the decrease in hydraulic loads, even though contaminant loads remained unchanged. Construction of a WNS in a new plant can reduce the initial capital investment cost related to the wastewater treatment.

The simplified WNS was obtained by eliminating interconnections with a flowrate of less than 4.0 m^3/h (Figure 3c). In this system, freshwater flowrate increased, from 263.8 to 268.7 m^3/h and from 52.5 to 53.8 m^3/h, for industrial and deionized water, respectively, because of the decrease in the amount of reused water. The wastewater generation rate also increased, from 62.6 to 68.9 m^3/h, because additional freshwater was supplied to meet the water requirement of the water-using operations.

The water network synthesis incurred tradeoffs between the reduction in freshwater consumption and increase in the quantities of all other contributors (Table 4). The total length and weight of the pipes in the WNS were 74.0% and 24.2% greater than those in the CWS, respectively. The total weights of pumps and motors, and the total volume of pump pits in the WNS were 263.4%, 30.6%, and 52.2% greater than those in the CWS, respectively. In the O&M stage, electricity consumption in the WNS was 7.8% higher than that in CWS. These increases occurred because the increases in the quantities of the pipe, pump, motor, pump pit, and electricity consumption required for the water reuse exceeded the decreases in quantities resulting from the decrease in freshwater consumption and wastewater generation.

The LCA showed that the WNS was environmentally more efficient than the CWS. The results of the environmental impact assessment are presented in Table 5 (the extent of environmental burdens is expressed by the value of the environmental effect score). The effect scores over the total life cycle of the WNS were lower than those of the CWS by 2.7–6.9% for the environmental impact categories. The increase or decrease in the environmental burdens of each contributor through the water network synthesis was in accordance with the results of the water system design; the effect scores of the WNS were greater than those of the CWS in the stages of construction and disposal, and those of the WNS were less in the O&M stage. The potentials of acidification and photochemical ozone creation throughout the life cycle of the WNS were equal to that of the CWNS, and the other potentials of the WNS were less than those of the CWS. Therefore, the tradeoffs between the environmental impact categories were not incurred through the water network synthesis.

The principal contributors to the environmental burdens during the life cycle were the consumptions of industrial and deionized water, as well as electricity; the other contributors were negligible (Table 5). The proportion of the effect scores of the contributor to the total effect scores summed over the life cycle in the environmental impact categories were from 31.7 to 62.0% and from 32.7 to 64.5% for industrial water, from 26.1 to 36.8% and from 21.0 to 31.2% for deionized water, and from 6.7 to 31.4% and from 7.8 to 36.2% for electricity used in the CWS and WNS, respectively. However, the effect scores of the pipes were negligible; its proportions to the total effect scores in the environmental impact

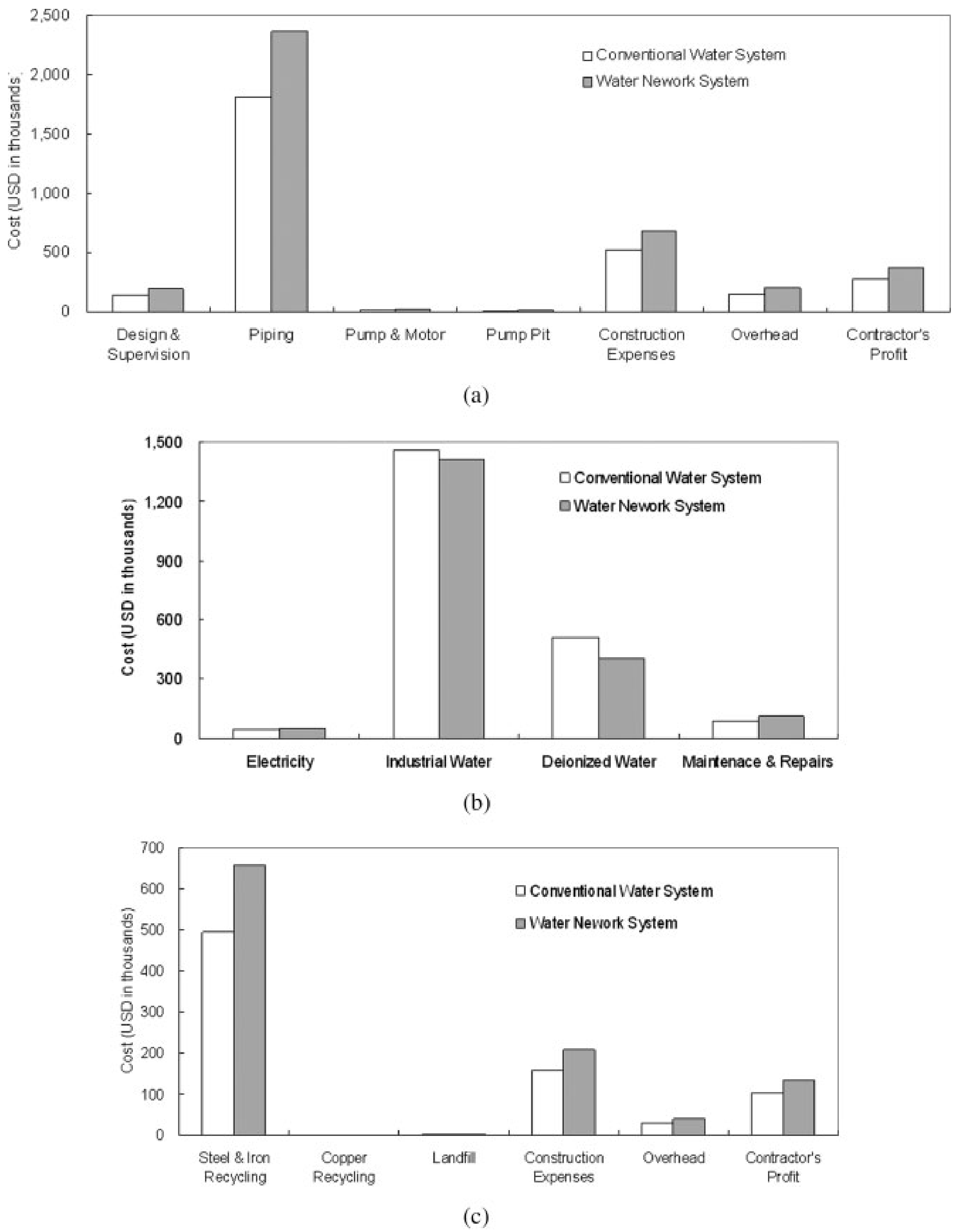

Figure 5. Cost estimation of all the contributors in the water network system (WNS) and conventional water system (WNS): (a) construction stage; (b) operations and maintenance (O&M) stage (on an annual basis); (c) disposal stage.

categories were from 0.3 to 2.4% and from 0.4 to 3.1% in the CWS and WNS, respectively. Therefore, the consumption of industrial and deionized water, as well as of electricity, should be included in the objective function of the mathematical optimization model, to obtain a more environmental-friendly WNS, and the tradeoffs among the environmental burdens from these principal contributors should be optimized to minimize the total environmental burdens of the WNS. In addition, most of the environmental burdens were generated in the O&M stages because of long-term effects over the service life; their proportions to the total effect scores were from 96.4 to 99.6% in the CWS and from 93.4 to 99.5% in the WNS for the environmental impact categories.

The LCC revealed that the WNS was economically more efficient than the CWS (Figure 4): water network synthesis reduced the life cycle cost by 1.7%. This was because the reduction of the O&M cost exceeded the increased construction cost required to build the WNS, even though the O&M cost decreased by 6.1% and the construction cost increased by 30.9%. The greatest proportion of the life cycle costs was incurred in the O&M stage. The O&M costs were 88.1% and 84.1% of the life cycle costs, but the construction costs were only 9.6% and 12.8% in the CWS and WNS, respectively. Costs of design, supervision, and disposal were not significant in the total life cycle.

The principal contributors to the economic costs during the life cycle were the costs of industrial and deionized water, and of piping (Figure 5). Note that the piping cost had significant effects on construction expenses, the contractor's overhead and profits, and on the costs of maintenance, repairs, and decommissioning which are proportional to a direct cost such as the piping cost.[25] However, the electricity cost for pumping was not more important than the piping cost, and even less than the maintenance and repairs cost, even though the consumption of electricity was a more significant contributor to environmental burdens than was the piping. This was because the environmental burdens from all industries required to generate electricity during the life cycle of the water systems were much more than those required for piping, and also because the piping cost included labor costs which were not included in the LCA. Therefore, the costs of industrial and deionized water, and of piping should be included in the objective function of the mathematical optimization model, to practically generate the most economical WNS. In addition, the most sustainable WNS can be obtained by using multi-objective optimization based on the model including the economic costs of industrial and deionized water, and of piping, as well as the environmental burdens from industrial and deionized water consumption, and from electricity consumption.

Conclusions

LCA and LCC analyses verified that the WNS had lower environmental burdens and economic costs than the CWS and was therefore more eco-efficient. These analyses estimated the effects of the tradeoffs in water system design on the environmental and economic performance of the WNS, and identified their principal contributors to the environmental burdens and economic costs.

In addition to the LCA and LCC analyses, this study showed that the extent of the contribution of each interconnection used for water reuse to the total environmental and economic performance needs to be additionally evaluated to effectively implement WNSs in real situation. The interconnections having the significant effect on the performance improvement can be employed to enhance the effectiveness of the total interconnections in the WNS; however, the interconnections having the negligible effect should be neglected to enhance the effectiveness of their construction and the efficiency of their O&M and disposal, as in the method revising the original WNS to the simplified WNS. For example, the interconnections with a high flowrate should be given priority for construction in implementing the WNS in the iron and steel plant, because the higher decrease in freshwater consumption induces the higher decrease in environmental burdens and economic costs.

This study provides fundamental information required for the application of ecodesign to process integration technologies, such as water, heat, and hydrogen network synthesis. Especially valuable to these process integration technologies is the discovery that electricity consumption required for the transfer of fluids is a principal contributor to environmental burdens, while piping cost is a principal contributor to economic costs, but not to environmental burdens.

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Appendix A: Mathematical Optimization Model for Water Network Synthesis

The mathematical formulation model used to optimize a water network system is as follows:

For the objective function to minimize the total freshwater cost,

$$\text{Minimize Cost}_w^t = \sum_{w \in W} \sum_{\text{opin} \in \text{OP}} F_{w,\text{opin}} UC_w \tag{A1}$$

Subject to the following:

For the overall mass balance of the entire water network system,

$$\sum_{w \in W} \sum_{\text{opin} \in \text{OP}} F_{w,\text{opin}} - \sum_{\text{ww} \in \text{WW}} F_{\text{opout,ww}} - \sum_{\text{op} \in \text{OP}} F_{L,\text{op}} = 0 \tag{A2}$$

For the mass balances of the mixers,

$$\sum_{w \in W} F_{w,\text{opin}} + \sum_{\text{opout} \in \text{OP}} F_{\text{opout,opin}} - F_{\text{opin}} = 0 \tag{A3}$$

$$\sum_{w \in W} F_{w,\text{opin}} C_{c,w} + \sum_{\text{opout} \in \text{OP}} F_{\text{opout,opin}} C_{c,\text{opout}} - F_{\text{opin}} C_{c,\text{opin}} = 0 \tag{A4}$$

For the mass balances of the operations,

$$F_{\text{opin}} - F_{L,\text{op}} - F_{\text{opout}} = 0 \tag{A5}$$

$$F_{\text{opin}} C_{c,\text{opin}} + M_{c,\text{op}} - F_{\text{opout}} C_{c,\text{opout}} = 0 \tag{A6}$$

For the mass balances of the splitters,

$$F_{\text{opout}} - \sum_{\text{opin} \in \text{OP}} F_{\text{opout,opin}} - F_{\text{opout,ww}} = 0 \tag{A7}$$

For the constraints of the flowrate and concentration on the operations,

$$F_{\text{opin}}^{\min} \leq F_{\text{opin}} \leq F_{\text{opin}}^{\max} \tag{A8}$$

$$C_{c,\text{opin}} \leq C_{c,\text{opin}}^{\max} \tag{A9}$$

$$C_{c,\text{opout}} \leq C_{c,\text{opout}}^{\max} \tag{A10}$$

For the constraints of the maximum flowrate on the freshwater sources,

$$\sum_{\text{opin} \in \text{OP}} F_{w,\text{opin}} - F_w^{\max} \leq 0 \tag{A11}$$

For the constraints on the prevention of local recycling,

$$F_{\text{opout,opin}} = 0, \text{ where the value of opout is the same as that of opin.} \tag{A12}$$

Appendix B: Notation Used for the Mathematical Optimization Model

Sets

$C = \{c|c$ is a contaminant in the water$\}$, $c = 1, 2, \ldots, Nc$
$W = \{w|w$ is freshwater available$\}$, $s = 1, 2, \ldots, Nm$
WW = {ww|ww is wastewater}, ww = 1, 2, …, Nn
OP = {op|op is a water-using operation}, op = 1, 2, …, Nn
= {opin|opin is a water-using operation}, opin = 1, 2, …, Nn
= {opout|opout is a water-using operation}, opout = 1, 2, …, Nn

Variables

$C_{c,\text{opin}}$ = concentration at the inlet of a water-using operation.
$C_{c,\text{opout}}$ = concentration at the outlet of a water-using operation.
$Cost_w^t$ = total cost per an hour for freshwater.
F_{opin} = flowrate at the inlet of a water-using operation.
F_{opout} = flowrate at the outlet of a water-using operation.
$F_{\text{opout,opin}}$ = flowrate from the outlet of a water-using operation to the inlet of other one.
$F_{\text{opout,ww}}$ = flowrate from the outlet of a water-using operation to wastewater.
$F_{w,\text{opin}}$ = flowrate from freshwater to a water-using operation.

Parameters

$C_{c,\text{opin}}^{\max}$ = maximum concentration at the inlet of a water-using operation.
$C_{c,\text{opout}}^{\max}$ = maximum concentration at the outlet of a water-using operation.
$C_{c,w}$ = freshwater concentration.
$F_{L,\text{op}}$ = water loss rate in a water-using operation.
$F_{\text{opin}}^{\min}$ = minimum flowrate at the inlet of a water-using operation.
$F_{\text{opin}}^{\max}$ = maximum flowrate at the inlet of a water-using operation.
$F_w^{\max}$ = maximum flowrate for freshwater.
$M_{c,\text{op}}$ = mass load of a contaminant.
UC_w = unit cost of freshwater.

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