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Analysis of effects of an objective function on environmental and economic performance of a water network system using life cycle assessment and life cycle costing methods

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Abstract

Water network synthesis has been used to conserve water resources and reduce economic costs. In this study, all contributors to environmental burdens and economic costs of water network systems were estimated to analyze the effects of objective functions on their environmental and economic performances. A total freshwater flowrate-minimized water network system (FWNS) and a total freshwater cost-minimized water network system (CWNS) were independently synthesized. Life cycle assessment and life cycle costing were performed to evaluate and compare the environmental and economic performances of the two water network systems. The CWNS was more environmentally and economically friendly than the FWNS because the CWNS was synthesized by minimizing the consumption of deionized water, which has higher unit cost and unit environmental effect scores than industrial water. Also this study demonstrated that the consumption rates of freshwater and electricity, as well as their unit environmental effect scores, should be used as principal contributors and weighting factors for the formulation of an objective function to generate the most environmentally friendly water network system, while the costs of piping and freshwater, as well as their unit costs, should be included to generate the most economically friendly system.

Keywords: Optimization; Objective function; Water network synthesis; Water reuse; Life cycle assessment; Life cycle costing

1. Introduction

Increasingly, sustainable development is required to conserve natural resources and achieve economic growth, so cleaner production has become important to simultaneously enhance environmental and economic competitiveness in almost all industries. The concept of an eco-design has been employed for processes, systems, utilities, products and services in the context of cleaner production. Water is an important target of eco-design because it is an essential resource for washing, cleaning and cooling, as well as being a product in itself, and because high costs are incurred in water treatment, water supply and wastewater treatment.

Water network synthesis technologies have been studied to reduce water consumption rates. Water network optimization was employed for the first time in a petroleum refinery plant in 1980 [1]. Since then, most studies of water network synthesis have focused on the development of methodologies to obtain global optima to mathematical programming models [2–7]. This is because non-convexities derived from bilinear variables in the mass balances of contaminants make it difficult to obtain global optima in nonlinear programming (NLP) and mixed-integer nonlinear programming (MINLP) models. The global optima of an MINLP model for wastewater minimization were also found using a genetic algorithm [8].

Various objective functions for mathematical optimization models have been used to reduce economic cost. Many of the objective functions used in previous works have minimized a single contributor, such as the total freshwater flowrate, number of interconnections, or fixed costs [5,8–11]. A few contributors to the economic cost were also used for the objective functions: the sum of freshwater costs and initial capital investment costs for pipes and wastewater treatment plants [4], and costs required for freshwater supply, water and wastewater treatment, pipes and sewers were included in the objective function [7]. However, the effects of the objective functions

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Nomenclature

Sets

C	$\{c \mid c$ is a contaminant in the water$\}$, $c = 1, 2, \ldots, N_c$
OP	$\{\mathrm{op} \mid \mathrm{op}$ is a water-using operation$\}$, $\mathrm{op} = 1, 2, \ldots, N_n$
OP	$\{\mathrm{opin} \mid \mathrm{opin}$ is a water-using operation$\}$, $\mathrm{opin} = 1, 2, \ldots, N_n$
OP	$\{\mathrm{opout} \mid \mathrm{opout}$ is a water-using operation$\}$, $\mathrm{opout} = 1, 2, \ldots, N_n$
W	$\{w \mid w$ is an available freshwater$\}$, $s = 1, 2, \ldots, N_m$
WW	$\{\mathrm{ww} \mid \mathrm{ww}$ is wastewater$\}$, $\mathrm{ww} = 1, 2, \ldots, N_n$

Variables

$C_{\mathrm{c,opin}}$	concentration at the inlet of a water-using operation
$C_{\mathrm{c,opout}}$	concentration at the outlet of a water-using operation
$\mathrm{Cost}_{\mathrm{w}}^{\mathrm{t}}$	total cost per 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
$F_{\mathrm{opout,opin}}$	flowrate from the outlet of a water-using operation to the inlet of a water-using operation
$F_{\mathrm{opout,ww}}$	flowrate from the outlet of a water-using operation to wastewater
$F_{\mathrm{w}}^{\mathrm{t}}$	total flowrate of freshwater
$F_{\mathrm{w,opin}}$	flowrate from freshwater source to a water-using operation

Parameters

$C_{\mathrm{c,opin}}^{\max}$	maximum concentration at the inlet of a water-using operation
$C_{\mathrm{c,opout}}^{\max}$	maximum concentration at the outlet of a water-using operation
$C_{\mathrm{c,w}}$	freshwater concentration
e	escalation rate
$F_{\mathrm{L,op}}$	water loss rate in a water-using operation
$F_{\mathrm{opin}}^{\max}$	maximum flowrate at the inlet of a water-using operation
$F_{\mathrm{opin}}^{\min}$	minimum flowrate at the inlet of a water-using operation
$F_{\mathrm{w}}^{\max}$	maximum flowrate for freshwater
i	interest rate
$M_{\mathrm{c,op}}$	mass load of a contaminant
P	payment
PV	present value
t	time
UC_{w}	unit cost of freshwater

on the environmental and economic performances of their water network systems have not been estimated in the previous works.

The environmental and economic performance can be improved by reducing environmental burdens and economic costs and increasing profits and benefits [12]. Life cycle assessment (LCA) and life cycle costing (LCC) methods have been used to evaluate the environmental and economic performance during the life cycle [13–16].

All contributors to environmental burdens and economic costs of water network systems were estimated to analyze the effects of objective functions on environmental and economic performances. One objective function minimized the total freshwater flowrate, which has often been used for the conservation of water resources in the context of environmental protection. The other minimized the total freshwater cost, which has been generally used for the reduction of operating costs in the context of profitability maximization. A total of 15 water-using operations were used to synthesize the two water network systems. The total freshwater flowrate-minimized system (FWNS) and the total freshwater cost-minimized water network system (CWNS) were generated from optimal solutions to their mathematical optimization models. The two water network systems were then specifically designed. Life cycle assessment (LCA) and life cycle costing (LCC) methods were employed to evaluate the environmental and economic performances of the FWNS and CWNS.

2. Methods

Water-using operations in an iron and steel plant were used for the water network syntheses. The limiting process data used for the water network syntheses are presented in Table 1. The distance matrix for the interconnections between the water sources and sinks, such as the freshwater sources, water-using operations and local wastewater treatment plants, is shown in Table 2. The capacities and concentrations of the industrial and deionized water of the freshwater sources used in this study are presented in Table 3.

2.1. *Water network synthesis*

A superstructure model was used to generate the FWNS and CWNS [17]. The model included all possible interconnections between water sources and sinks: from the outlet of one operation to the inlet of the others, as well as between freshwater sources and water-using operations. However, local recycling which returns the effluent of an operation into the influent of the same operation was prohibited, to reduce the electricity cost derived from an excessive pumping flowrate [17]. Freshwater sources were not directly connected to local wastewater treatment plants, to prevent the loss of freshwater. It was assumed that mixers combined all possible streams into one stream and that splitters divided a given stream into all possible streams flowing to water sinks.

The objective functions used to synthesize the FWNS and CWNS were formulated for the minimization of the total flowrate and cost of the freshwater supplied for the water-using operations. The mathematical optimization models formulated for the superstructure model are as follows.

Table 1
Limiting process data used for the water network syntheses

Operation	Contaminant	$C^{\max}_{\text{c,opin}}$ (mg/L)	$C^{\max}_{\text{c,opout}}$ (mg/L)	M_{op} (kg/h)	$F_{\text{L,op}}$ (m^3/h)	$F^{\min}_{\text{opin}}$ (m^3/h)	$F^{\max}_{\text{opin}}$ (m^3/h)
OP 1	CODcr	50	600	6.5	70.7	80	150
	SS	20	200	2.0			
	Cl^-	90	1100	12.9			
OP 2	CODcr	30	500	3.3	49.7	50	90
	SS	5	100	0.5			
	Cl^-	120	2300	16.4			
OP 3	CODcr	40	1500	5.4	6.0	10	50
	SS	2	70	0.2			
	Cl^-	150	6000	20.7			
OP 4	CODcr	30	500	3.5	38.8	40	90
	SS	2	50	0.3			
	Cl^-	50	750	6.2			
OP 5	CODcr	20	250	2.3	36.6	40	90
	SS	3	50	0.4			
	Cl^-	20	300	3.0			
OP 6	CODcr	20	300	2.8	25.3	30	80
	SS	4	60	0.5			
	Cl^-	20	300	2.8			
OP 7	CODcr	10	70	0.9	3.8	10	60
	SS	2	20	0.2			
	Cl^-	5	70	0.7			
OP 8	CODcr	23	400	3.2	8.3	10	70
	SS	5	80	0.6			
	Cl^-	10	200	1.5			
OP 9	CODcr	29	900	4.0	14.5	10	70
	SS	3	100	0.4			
	Cl^-	60	1600	7.5			
OP 10	CODcr	20	180	2.1	14.5	20	70
	SS	4	50	0.5			
	Cl^-	50	500	7.2			
OP 11	CODcr	30	250	3.8	24.3	40	200
	SS	20	100	2.0			
	Cl^-	1	10	0.1			
OP 12	CODcr	10	160	1.5	8.8	10	60
	SS	2	25	0.2			
	Cl^-	1	5	0.0			
OP 13	CODcr	40	350	5.3	0	10	60
	SS	5	100	1.4			
	Cl^-	90	700	12.1			
OP 14	CODcr	30	250	3.4	3.1	10	60
	SS	1	50	0.6			
	Cl^-	80	750	11.5			
OP 15	CODcr	30	300	4.5	0.8	10	40
	SS	5	15	0.1			
	Cl^-	3	40	0.4			

For the objective function used for the FWNS to minimize the total freshwater flowrate in the context of the conservation of water resources,

$$\text{Minimize}\quad F^{\text{t}}_{\text{w}} = \sum_{w \in W} \sum_{\text{opin} \in \text{OP}} F_{\text{w,opin}} \tag{1}$$

For the objective function used for the CWNS to minimize the total freshwater cost in the context of cost reduction,

$$\text{Minimize}\quad \text{Cost}^{\text{t}}_{\text{w}} = \sum_{w \in W} \sum_{\text{opin} \in \text{OP}} F_{\text{w,opin}} \text{UC}_{\text{w}} \tag{2}$$

Subject to the followings:

Table 2
Distance matrix (FW: freshwater, OP: water-using operation, TP: local wastewater treatment plant, unit: m)

	FW 1	FW 2	OP 1	OP 2	OP 3	OP 4	OP 5	OP 6	OP 7	OP 8	OP 9	OP 10	OP 11	OP 12	OP 13	OP 14	OP 15
OP 1	2250	280															
OP 2	2060	1010	1010														
OP 3	4820	4850	4880	4930													
OP 4	4960	4930	4980	4980	110												
OP 5	2090	410	460	280	4330	4140											
OP 6	920	1010	1030	140	4170	4120	650										
OP 7	950	1090	1140	170	4200	4170	680	140									
OP 8	980	1140	1200	220	4250	4060	710	170	90								
OP 9	820	1600	1680	550	4040	4010	550	220	140	170							
OP 10	950	1680	1710	460	4120	4090	680	410	330	360	330						
OP 11	4550	4580	4660	4390	410	380	4280	3900	3820	3850	3900	3820					
OP 12	4600	4660	4710	4470	490	410	4330	4010	3930	3960	3930	3850	220				
OP 13	2660	2410	2490	2220	2440	2360	2390	1740	1660	1680	2010	1930	1950	1930			
OP 14	2710	2490	2550	2280	2520	2440	2440	1790	1710	1740	2030	1950	1930	1900	250		
OP 15	2850	2580	2600	2300	2580	2550	2580	1820	1740	1760	2090	2010	1870	1840	190	140	
TP 1			460	520	4830	4880	300	520	620	570	620	650	4660	4740	2870	2820	2930
TP 2			4770	4500	410	460	4390	4010	4010	3960	3990	4020	300	330	2010	2060	2120
TP 3			4820	4580	360	410	4440	4120	4110	4060	4090	4120	330	280	1980	2030	1980
TP 4			2680	2410	2150	2200	2580	1930	1920	1870	1900	1930	2090	2060	320	300	350
TP 5			2630	2360	2200	2250	2530	1880	1870	1820	1850	1880	2140	2110	400	350	300
TP 6			1910	660	4320	4290	880	610	530	560	530	250	4020	4050	2130	2150	2210

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

$$\sum_{w \in W} \sum_{\text{opin} \in \text{OP}} F_{\text{w,opin}} - \sum_{\text{ww} \in \text{WW}} F_{\text{opout,ww}} - \sum_{\text{op} \in \text{OP}} F_{\text{L,op}} = 0 \quad (3)$$

For the mass balances of the mixers,

$$\sum_{w \in W} F_{\text{w,opin}} + \sum_{\text{opout} \in \text{OP}} F_{\text{opout,opin}} - F_{\text{opin}} = 0 \quad (4)$$

$$\sum_{w \in W} F_{\text{w,opin}} C_{\text{c,w}} + \sum_{\text{opout} \in \text{OP}} F_{\text{opout,opin}} C_{\text{c,opout}} - F_{\text{opin}} C_{\text{c,opin}} = 0 \quad (5)$$

For the mass balances of the operations,

$$F_{\text{opin}} - F_{\text{L,op}} - F_{\text{opout}} = 0 \quad (6)$$

$$F_{\text{opin}} C_{\text{c,opin}} + M_{\text{c,op}} - F_{\text{opout}} C_{\text{c,opout}} = 0 \quad (7)$$

For the mass balances of the splitters,

$$F_{\text{opout}} - \sum_{\text{opin} \in \text{OP}} F_{\text{opout,opin}} - F_{\text{opout,ww}} = 0 \quad (8)$$

For the constraints of the flowrates and concentrations on the operations,

$$F_{\text{opin}}^{\min} \le F_{\text{opin}} \le F_{\text{opin}}^{\max} \quad (9)$$

Table 3
Capacities and concentrations of freshwater sources

Freshwater	$F_{\text{w}}^{\max}$ (m^3/h)	$C_{\text{c,w}}$ (mg/L)		
		CODcr	SS	Cl^-
FW 1: Industrial water	700	0	0	15
FW 2: Deionized water	250	0	0	0

$$C_{\text{c,opin}} \le C_{\text{c,opin}}^{\max} \quad (10)$$

$$C_{\text{c,opout}} \le C_{\text{c,opout}}^{\max} \quad (11)$$

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

$$\sum_{\text{opin} \in \text{OP}} F_{\text{w,opin}} - F_{\text{w}}^{\max} \le 0 \quad (12)$$

For the constraints required to prohibit local recycling,

$$F_{\text{opout,opin}} = 0 \quad (13)$$

where the value of opout is the same as that of opin.

The FWNS and CWNS were generated from the optimal solutions to the above NLP models. GAMS/MINOS [18] was used as an NLP solver to obtain the optima of the models. Linear Programming (LP) models generated by fixing the flowrates or concentrations in the NLP models were used to determine the initial points of the NLP models, because the non-convexities derived from the bilinear variables in the mass balances of contaminants make it difficult to obtain the global optima. The streams of wastewater were combined and connected to the local wastewater treatment plants with respect to real field situations in the plant.

2.2. Water system design

The FWNS and CWNS were specifically designed for the estimation of the LCA and LCC. The original water network systems generated from the optimal solutions to the mathematical optimization models were simplified by eliminating inefficient interconnections having a flowrate of less than 4 m^3/h. Freshwater with the same flowrate was assumed to be added to the water-using operations to replace the reused water supplied through the inefficient interconnections.

The pipe diameter and head loss were calculated simultaneously with the flowrate and pipe length. The pipe length was obtained from the distance between the water source and sink. The head loss was calculated using the Darcy–Weisbach equation [19]. The maximum head loss criteria were employed for the selection of the nominal pipe diameter and were set at 2.0 and 0.2 $\mathrm{kg_f/cm^2}$ for pumping and gravity flows, respectively. Carbon steel was selected as the pipe material. The Korean Standard, KS D3507, was used to obtain the specific data, such as the nominal diameter, wall thickness and weight. The minimum nominal pipe diameter was set at 1 in. for the sake of simplicity of the design.

The pumps and electric motors were specified in detail in relation to the flowrate and water head requirement. The discharge pressure of the pump was determined by summing the head losses in the pipes and the water pressure required for the water-using operation. The water pressures required at the end of pipes were assumed to be 2.5 and 1.0 $\mathrm{kg_f/cm^2}$ for the water-using operations and local wastewater treatment plants, respectively.

Pump pits were required for the storage of the wastewater prior to its pumping to the local wastewater treatment plants. The hydraulic retention times for the pump pits were set at 30 min.

2.3. *Life cycle assessment*

An LCA was performed to evaluate and compare the environmental burdens associated with the FWNS and CWNS. All the environmental burdens generated from the inputs and outputs throughout the life cycle were taken into account by assessing the results of the designs of the two water network systems. The LCA procedure was performed in accordance with the ISO 14040 series of standards [20]: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation.

The goal and scope definition included the goal, system, function, functional unit, reference flow, system boundaries, allocation, data qualities and assumptions. The goal of this LCA was to estimate the effects of the objective functions used for the water network syntheses on the environmental performances of the water network systems. The system and its function were defined as each water network system required to supply industrial and deionized water for the water-using operations shown in Table 1 and to transfer the generated wastewater to the local wastewater treatment plants. The functional unit was defined as the water network system required for a total of 15 water-using operations during its life cycle (15 years), and the reference flow was set to one unit of the water network system. The system boundaries included all the contributors to the environmental burdens from the water network system, with the exception of the freshwater storage basins and local wastewater treatment plants, both of which could be neglected as the same baseline in a comparison. The emissions to water could also be excluded because the mass loads of the contaminants from the two water network systems were the same, even though there was a difference between their wastewater generation flowrates. In other words, it was assumed that the environmental burdens from the wastewater treatment were proportional to the contaminant loads. The allocation was not required in this LCA. The same data qualities were used for the comparative assessment, because most of the data were calculated from the same design criteria and assumptions. The service life of the two water network systems was assumed to be 15 years with respect to the lifetime of the pipes and mechanical equipment.

A life cycle inventory analysis (LCI) was performed to quantify all the inputs and outputs associated with each water network system throughout its construction, operations and maintenance (O&M) and disposal stages. The GaBi 4.0 [21] and Ecoinvent v1.2 [22] databases were used for the LCI. The inventory in the construction stage included the manufacture of the pipes, pumps and motors, the construction of the pump pits, the associated transportations and piping works. The environmental burdens from the consumptions of utilities, such as industrial and deionized water and electricity, 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.

A life cycle impact assessment (LCIA) was performed to evaluate the significance of potential environmental impacts on the basis of the results of the LCI. The CML 2001 methodology [21] was used for the classification and characterization to evaluate the environmental effect scores from all the contributors in the two water network systems. The environmental impact categories consist of abiotic depletion, acidification, eutrophication, freshwater aquatic ecotoxicity, global warming, human toxicity, marine aquatic ecotoxicity, ozone layer depletion, photochemical ozone creation, radioactive radiation, and terrestrial ecotoxicity.

A life cycle interpretation was performed to comprehensively estimate the results of the preceding steps. The environmental effect scores of all the contributors in the FWNS were compared with those of the CWNS, to examine the effects of their objective functions on tradeoffs among the environmental effect scores of all the contributors. Principal contributors to the environmental burdens were also identified. The total effect scores of all the categories in the FWNS were also compared to those in the CWNS, to estimate the effects of the objective functions on their environmental performances. The maximum effect score in each category of the two water network systems was set as a baseline used to normalize and compare the total effect scores of the FWNS and CWNS.

2.4. *Life cycle costing*

The LCC was employed to estimate the economic performances of the two water network systems. Their economic performances were measured by estimating total economic costs incurred throughout the life cycle; their external costs were not taken into account in the LCC because their environmental impacts were evaluated in the LCA. The life cycle of the LCC was divided into four categories: design and supervision, construction, O&M and disposal. The design and supervision stage consisted of the basic and detailed designs, as well as supervision. The cost in 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. The O&M cost included the consumption of industrial and deionized water, electricity, and maintenance and repairs. The cost in the disposal stage was divided into the costs for recycling, landfill and construction expenses, as well as the contractor's overhead and profits. However, the costs of wastewater treatment were not included in the LCC because it was assumed that the same cost was required to treat the same contaminant loads, as mentioned in the scope definition of the LCA. The cost estimation was performed using databases consisting of price and cost information [23,24]. The service life for the LCC was set at 15 years, as in the LCA.

All of the contributors to the life cycle cost of the FWNS were compared to those of the CWNS to examine the effects of the objective functions on tradeoffs among the economic costs of all contributors. The life cycle costs of the two water network systems were also compared to each other to estimate the effects of the objective functions on their economic performances. After the future costs were discounted to present values taking into account the time value of money, the present values were summed to obtain the life cycle cost of each water network system. Because the O&M cost recurs annually and the disposal cost is incurred at the end of the service life, they were converted to present values to be equally estimated and compared to the initial capital investment cost [25]. The present value was estimated using the following equation:

$$\mathrm{PV} = \frac{P(1+e)^t}{(1+i)^t} \tag{14}$$

The interest rate was set at 5.7%, the yield of treasury bonds (5-years) over the last 10 years in South Korea [26], and the escalation rate was assumed to be the 3.0% targeted by the Bank of Korea for the period between 2004 and 2006 [27].

3. Results and discussion

The FWNS and CWNS were independently generated from the optimal solutions to the mathematical optimization models, using the process limiting and freshwater source data, as illustrated in Fig. 1.

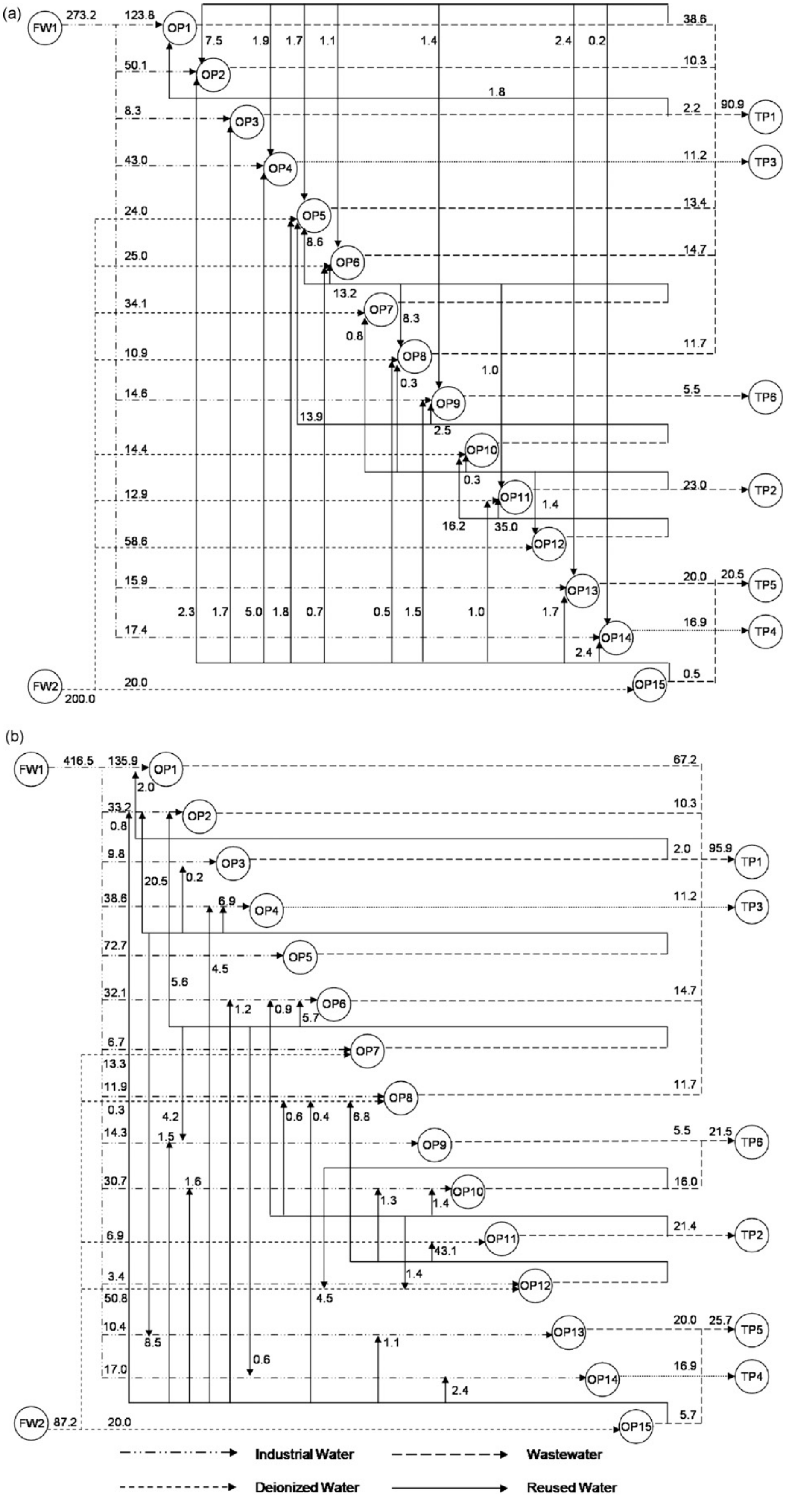
The design results of the two systems are summarized in Table 4, showing that the quantities of all the contributors, except the consumption rate of deionized water, were greater in the CWNS than in the FWNS. The total length and weight of the pipes in the CWNS were 28.0 and 5.0% greater than those in the FWNS, respectively. This was mainly because both industrial and deionized water were supplied for operations 7 and 11 in the CWNS, and operation 5 was supplied with deionized water in the FWNS but with industrial water in the CWNS. The number of the efficient interconnections with a flowrate of greater than 4 m^3/h in the CWNS was also greater than that in the FWNS. The total weights of pumps and motors in the CWNS were 4.9 and 11.7% greater than those in the FWNS, and the total volume of pump pits in the CWNS was 8.5% greater than that in the FWNS. This was because the flowrates of the freshwater and reused water in the CWNS were higher than those in the FWNS. The total freshwater consumption rate of the CWNS was 4.6% higher than that of the FWNS, because the objective function used for the FWNS minimized the total freshwater flowrate. The total flowrate of industrial water in the CWNS was 47.3% higher than that in the FWNS, while the total flowrate of deionized water in the CWNS was 56.4% lower than that in the FWNS. This was because the objective function used for the CWNS was formulated to drive the consumption of industrial water (\$0.60 U.S./m^3) rather than that of deionized water (\$0.85 U.S./m^3), to minimize the total freshwater cost. The total wastewater generation flowrate in the FWNS was 10.9% lower than that in the CWNS because of the lower consumption of total freshwater in the FWNS. This would reduce operating costs and enhance removal efficiencies in the existing local wastewater treatment plants, because of the decrease of the hydraulic loads, even though the contaminant loads remained unchanged. However, the reduction of the costs derived from the lower wastewater generation rate was not considered in this study, because the costs were assumed to be proportional to the contaminant loads treated. The electricity consumption rate in the FWNS was 3.5% greater than that in the CWNS, which was in accordance with the design results of the pumps and motors.

Table 4
Summary of the design results for the total freshwater flowrate-minimized water network system (FWNS) and total freshwater cost-minimized water network system (CWNS)

Item	FWNS	CWNS
Pipe		
Length (m)	57,080	73,090
Weight (kg)	943,221	990,638
Pump		
Weight (kg)	3840	4027
Motor		
Weight (kg)	1690	1887
Pump pit		
Volume (m^3)	153	166
Freshwater consumption rate		
Industrial water (m^3/h)	293.1	431.6
Deionized water (m^3/h)	205.3	89.6
Total (m^3/h)	498.4	521.2
Electricity consumption rate (kW)	159.8	165.4
Wastewater generation rate (m^3/h)	198.4	220.0

The two water network systems were simplified for the estimation of the LCA and LCC by eliminating inefficient interconnections with a flowrate of less than 4 m^3/h.

The effect scores of all the contributors to the environmental burdens from the FWNS and CWNS were evaluated on the basis of the LCA, as shown in Table 5. The effect scores of all the contributors, except the consumption rate of deionized water, were greater in the CWNS than in the FWNS, which was in accord with the design results resulting from the characteristics of their objective functions. It should be noted that each objective func-


(a)
FW1
273.2
123.8
OP1
38.6
7.5
1.9
1.7
1.1
1.4
2.4
0.2
50.1
OP2
10.3
1.8
8.3
OP3
2.2
90.9
TP1
43.0
OP4
11.2
TP3
24.0
OP5
13.4
8.6
25.0
OP6
14.7
13.2
34.1
OP7
8.3
0.8
10.9
OP8
11.7
1.0
0.3
14.6
OP9
5.5
TP6
13.9
2.5
14.4
OP10
0.3
12.9
OP11
23.0
TP2
1.4
16.2
35.0
58.6
OP12
15.9
OP13
20.0
20.5
TP5
2.3
1.7
5.0
1.8
0.7
0.5
1.5
1.0
1.7
17.4
OP14
16.9
TP4
2.4
FW2
200.0
20.0
OP15
0.5
(b)
FW1
416.5
135.9
OP1
67.2
2.0
33.2
OP2
10.3
0.8
9.8
OP3
2.0
95.9
TP1
0.2
20.5
38.6
6.9
OP4
11.2
TP3
72.7
OP5
4.5
5.6
32.1
1.2
0.9
OP6
14.7
5.7
6.7
OP7
13.3
11.9
OP8
11.7
0.3
0.6
0.4
6.8
4.2
14.3
1.5
OP9
5.5
21.5
TP6
30.7
1.6
1.3
OP10
16.0
1.4
6.9
OP11
21.4
TP2
43.1
1.4
3.4
OP12
4.5
50.8
10.4
OP13
20.0
25.7
TP5
8.5
1.1
0.6
17.0
OP14
16.9
TP4
2.4
FW2
87.2
20.0
OP15
5.7
Industrial Water
Wastewater
Deionized Water
Reused Water

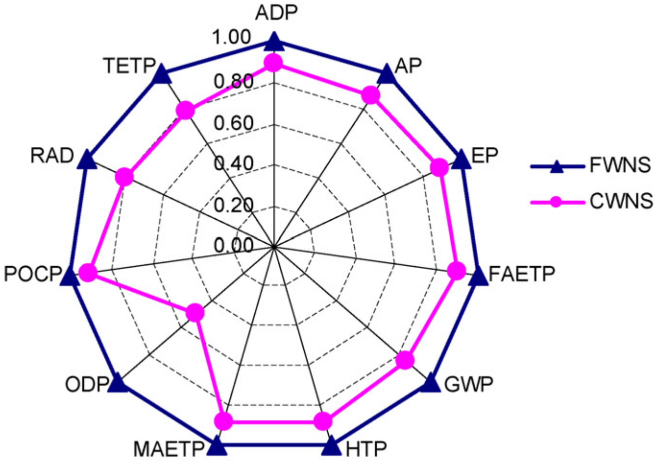


Fig. 2. Environmental effect scores of the total freshwater flowrate-minimized water network system (FWNS) and total freshwater cost-minimized water network system (CWNS) during the total life cycle. The CML 2001 methodology was employed for the classification and characterization. The effect scores of the FWNS and CWNS in each category were divided by a higher score between their scores (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]; ODP: Ozone Layer depletion potential (steady state) [kg R11-equivalents]; POCP: photochemical ozone creation potential [kg Ethene-equivalents]; RAD: radioactive radiation [DALY]; TETP: terrestrial ecotoxicity potential [kg DCB-equivalents]; DCB: 1,4-dichlorobenzene).

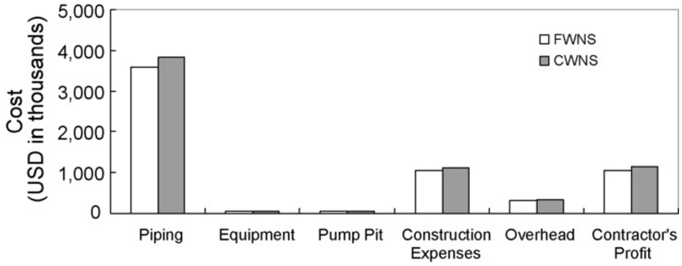


Fig. 3. Cost estimation of all the contributors in the construction stage (FWNS: total freshwater flowrate-minimized water network system, CWNS: total freshwater cost-minimized water network system).

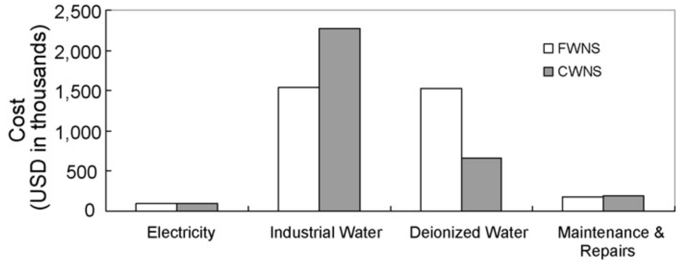


Fig. 4. Cost estimation of all the processes on an annual basis in the operations and maintenance (O&M) stage (FWNS: total freshwater flowrate-minimized water network system, CWNS: total freshwater cost-minimized water network system).

tion engendered different tradeoffs among the effect scores of the contributors. The proportions of the effect scores of the contributors to the total effect scores summed over the life cycle in the environmental impact categories, except for the ozone layer depletion potential, were from 16.3 to 38.4% and from 30.5 to 63.3% for industrial water, from 42.5 to 56.6% and from 20.9 to 31.0% for deionized water, and from 7.7 to 30.0% and from 9.0 to 39.4% for electricity in the FWNS and CWNS, respectively. The effect scores from the consumption of deionized water were dominant in the category of the ozone layer depletion potential; their proportions to the total effect scores were 93.0 and 81.8% in the FWNS and CWNS, respectively. The effect scores from the other contributors were negligible. Therefore, the principal contributors of the two systems were the consumption of industrial and deionized water, as well as electricity. It should be noted that the unit effect scores of deionized water were greater than those of industrial water when the effect scores from industrial and deionized water were compared to their flowrates in the FWNS.

The total environmental effect scores were estimated in each stage and during the total life cycle, as shown in Table 5 and Fig. 2. The proportions of the effect scores in the O&M stage to the total effect scores were from 95.8 to 99.7% and from 95.0 to 99.6% for the FWNS and CWNS, respectively. The effect scores of the CWNS were less than those of the FWNS in the O&M stage by from 10.1 to 50.6% because the effect scores from the consumption of deionized water in the CWNS were greatly reduced. This was because the objective function used for the CWNS drove the decrease of the flowrate of deionized water, which has higher unit effect scores. The total effect scores in the construction and disposal stages were negligible, when compared to those in the O&M stage. The total environmental burdens of the CWNS during the life cycle were less than those of the FWNS, as shown in Fig. 2. Therefore, the CWNS was more environmentally friendly than the FWNS, even though the FWNS was synthesized to minimize the total freshwater flowrate for the conservation of water resources. This was because the decrease of the effect scores resulting from the decrease in the consumption of deionized water significantly decreased the total effect scores throughout the life cycle. Therefore, it should be noted that the weighting factors of the principal contributors, such as unit effect scores, should be used for the formulation of an objective function to synthesize the most environmentally friendly water network system. The unit costs of the freshwater in the objective function required for the CWNS were used as the weighting factors, showing results similar to those expected when the unit environmental effect scores were employed in the objective function.

Fig. 1. Comparison of the water network systems: (a) total freshwater flowrate-minimized water network system (FWNS) generated with the objective function minimizing the total flowrate of freshwaters; (b) total freshwater cost-minimized water network system (CWNS) generated with the objective function minimizing the total cost of freshwaters (FW: freshwater, OP: water-using operation, TP: local wastewater treatment plant, unit: m^3/h).

Table 5
Results of the life cycle impact assessment for the total freshwater flowrate-minimized water network system (FWNS) and total freshwater cost-minimized water network system (CWNS) in each life cycle stage

	ADP	AP	EP	FAETP	GWP	HTP	MAETP	ODP	POCP	RAD	TETP
Construction											
Pipe											
FWNS	2.1E+03	1.1E+03	2.2E+02	1.4E+05	2.6E+05	8.7E+05	1.6E+08	2.6E−02	2.9E+02	1.6E−03	2.1E+03
CWNS	2.2E+03	1.1E+03	2.4E+02	1.4E+05	2.7E+05	9.2E+05	1.7E+08	2.7E−02	3.1E+02	1.7E−03	2.2E+03
Pump											
FWNS	8.2E+00	2.5E+00	3.0E−01	6.1E+00	1.3E+03	8.1E+02	7.4E+04	3.0E−05	4.9E−01	1.2E−06	5.5E−01
CWNS	8.6E+00	2.7E+00	3.1E−01	6.4E+00	1.4E+03	8.5E+02	7.8E+04	3.2E−05	5.1E−01	1.3E−06	5.8E−01
Motor											
FWNS	1.3E+01	4.8E+01	5.9E−01	8.0E+01	1.9E+03	2.1E+03	6.3E+05	1.8E−04	2.9E+00	8.1E−05	7.9E+00
CWNS	1.4E+01	5.4E+01	6.6E−01	8.9E+01	2.2E+03	2.3E+03	7.1E+05	2.0E−04	3.3E+00	9.0E−05	8.8E+00
Pump pit											
FWNS	3.7E+01	4.2E+01	4.3E+01	3.8E+02	1.7E+04	1.8E+03	5.5E+05	5.6E−04	4.7E+00	3.4E−05	3.3E+01
CWNS	3.9E+01	4.4E+01	4.6E+01	4.0E+02	1.8E+04	1.8E+03	5.8E+05	5.9E−04	4.9E+00	3.6E−05	3.5E+01
Total											
FWNS	2.1E+03	1.2E+03	2.7E+02	1.4E+05	2.8E+05	8.8E+05	1.6E+08	2.6E−02	3.0E+02	1.8E−03	2.1E+03
CWNS	2.2E+03	1.2E+03	2.8E+02	1.4E+05	2.9E+05	9.2E+05	1.7E+08	2.8E−02	3.2E+02	1.9E−03	2.2E+03
O&M											
Industrial water											
FWNS	7.6E+04	7.5E+04	1.2E+04	2.6E+06	1.4E+07	1.1E+07	7.5E+09	7.1E−01	7.7E+03	1.9E−01	1.1E+05
CWNS	1.1E+05	1.1E+05	1.8E+04	3.8E+06	2.1E+07	1.7E+07	1.1E+10	1.0E+00	1.1E+04	2.7E−01	1.7E+05
Deionized water											
FWNS	1.3E+05	1.1E+05	1.7E+04	3.8E+06	2.8E+07	1.7E+07	1.2E+10	1.6E+01	1.0E+04	4.5E−01	3.7E+05
CWNS	5.7E+04	5.0E+04	7.3E+03	1.7E+06	1.2E+07	7.4E+06	5.4E+09	7.0E+00	4.5E+03	2.0E−01	1.6E+05
Electricity											
FWNS	9.1E+04	2.4E+04	2.5E+03	1.3E+06	1.5E+07	5.1E+06	6.9E+09	4.1E−01	2.3E+03	1.5E−01	2.1E+05
CWNS	9.4E+04	2.5E+04	2.6E+03	1.3E+06	1.6E+07	5.3E+06	7.1E+09	4.2E−01	2.4E+03	1.6E−01	2.2E+05
Maintenance and repairs											
FWNS	9.6E+02	5.2E+02	1.2E+02	6.2E+04	1.2E+05	4.0E+05	7.3E+07	1.2E−02	1.4E+02	7.9E−04	9.5E+02
CWNS	1.0E+03	5.5E+02	1.3E+02	6.5E+04	1.3E+05	4.2E+05	7.6E+07	1.2E−02	1.4E+02	8.4E−04	1.0E+03
Total											
FWNS	3.0E+05	2.1E+05	3.2E+04	7.7E+06	5.8E+07	3.4E+07	2.7E+10	1.7E+01	2.0E+04	7.9E−01	6.9E+05
CWNS	2.6E+05	1.9E+05	2.8E+04	6.8E+06	4.9E+07	3.0E+07	2.4E+10	8.5E+00	1.8E+04	6.3E−01	5.5E+05
Disposal											
Steel and iron recycling											
FWNS	6.9E+03	3.1E+03	2.5E+02	1.1E+03	7.3E+05	4.5E+05	2.0E+08	5.1E−02	4.8E+02	3.4E−03	2.3E+02
CWNS	7.3E+03	3.3E+03	2.7E+02	1.2E+03	7.7E+05	4.7E+05	2.1E+08	5.4E−02	5.0E+02	3.6E−03	2.4E+02
Copper recycling											
FWNS	3.4E+00	4.3E+01	1.9E−01	2.0E+05	4.1E+02	7.6E+02	4.0E+07	1.4E−04	2.3E+00	7.4E−05	2.6E+00
CWNS	3.7E+00	4.8E+01	2.1E−01	2.2E+05	4.6E+02	8.5E+02	4.4E+07	1.5E−04	2.5E+00	8.2E−05	3.0E+00
Landfill											
FWNS	1.5E+01	1.9E+01	1.0E+01	5.2E+01	1.3E+03	5.2E+02	1.3E+05	3.5E−04	2.7E+00	2.6E−06	4.0E+00
CWNS	1.5E+01	1.9E+01	1.1E+01	5.5E+01	1.4E+03	5.5E+02	1.3E+05	3.7E−04	2.8E+00	2.7E−06	4.2E+00
Total											
FWNS	6.9E+03	3.2E+03	2.6E+02	2.0E+05	7.4E+05	4.5E+05	2.4E+08	5.2E−02	4.8E+02	3.5E−03	2.4E+02
CWNS	7.3E+03	3.4E+03	2.8E+02	2.2E+05	7.7E+05	4.7E+05	2.6E+08	5.4E−02	5.1E+02	3.7E−03	2.5E+02

The 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]; ODP: ozone layer depletion potential (steady state) [kg R11-equivalents]; POCP: photochemical ozone creation potential [kg Ethene-equivalents]; RAD: radioactive radiation [DALY]; TETP: terrestrial ecotoxicity potential [kg DCB-equivalents]; DCB: 1,4-dichlorobenzene).

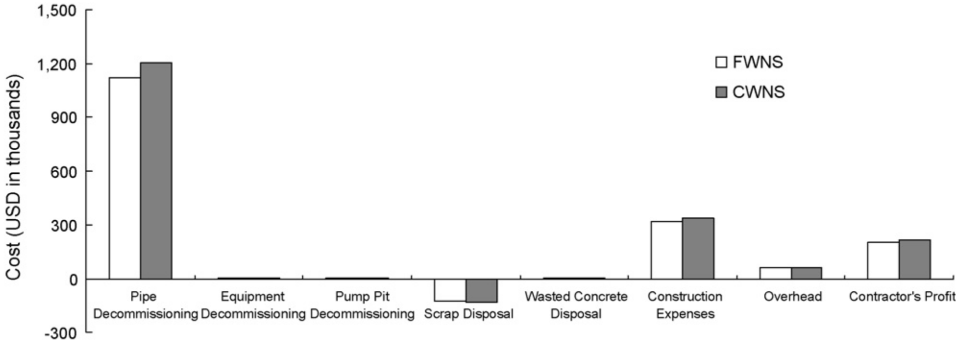


Fig. 5. Cost estimation of all the contributors in the disposal stage (FWNS: total freshwater flowrate-minimized water network system, CWNS: total freshwater cost-minimized water network system).

Each objective function used for the two water network systems resulted in different tradeoffs among the costs of their contributors over the life cycle. Fig. 3 shows the cost estimation in the construction stage. The construction cost of the CWNS was greater than that of the FWNS because the water network of the CWNS was more complicated to fully utilize industrial water and reused water. The piping cost was the principal contributor to the construction cost and had significant effects on the construction expenses, as well as the contractor's overhead and profits, which are calculated on the basis of the piping cost [24]. Fig. 4 shows the results of the cost estimation performed on an annual basis in the O&M stage. The effects of the objective functions on the costs of the freshwater and electricity were similar to those on their environmental effect scores shown in Table 5. The O&M cost of the CWNS was less than that of the FWNS. The FWNS was synthesized by focusing on the reduction of the flowrate of industrial water rather than that of deionized water, because its objective function was formulated to reduce the total freshwater flowrate, regardless of the unit costs. However, the objective function used for the CWNS minimized the flowrate of deionized water, with its higher unit cost, rather than that of industrial water. The maintenance and repairs cost contributed more to the O&M cost than the electricity cost, because of the complexity of the water networks. Fig. 5 shows all the costs incurred in the disposal stage. The disposal cost of the CWNS was higher than that of the FWNS, which was in accord with the results of the cost estimation in the construction stage. The pipe decommissioning costs were the principal contributors to the disposal costs. Revenues were incurred from the recycling of iron and steel scraps in the disposal of the pipes and equipment. It was shown that the piping cost had significant effects on the construction expenses, the contractor's overheads and profits, the maintenance and repairs cost, and the pipe decommissioning cost during the life cycle.

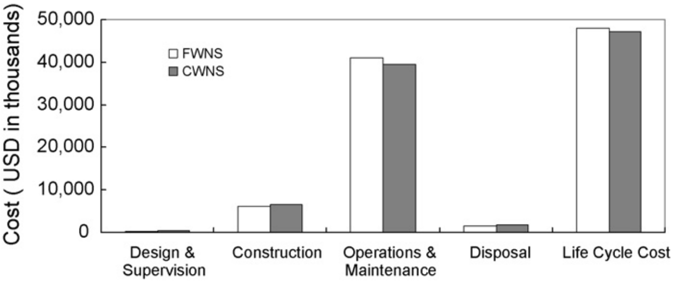


Fig. 6. Cost estimation of each life cycle stage and the life cycle cost. Future costs were discounted to present values (FWNS: total freshwater flowrate-minimized water network system, CWNS: total freshwater cost-minimized water network system).

The total costs in each life cycle stage and the life cycle costs were calculated to estimate the economic performances of the two water network systems, as shown in Fig. 6. The life cycle cost of the FWNS was greater than that of the CWNS. Therefore, the CWNS was more economically friendly than the FWNS, which was in accord with the goal of the objective function used for the CWNS. This was because the reduction of the O&M cost resulting from the decrease in the consumption of deionized water in the CWNS had the most significant effect on the life cycle cost. It should be noted that all of the principal contributors to the life cycle cost, such as the piping and freshwater and their weighting factors, such as the unit costs, should be used to formulate an objective function required to generate the most economically friendly water network system. The costs incurred in the design and supervision and disposal stage were negligible when compared to those in the construction and O&M stages.

4. Conclusions

The effects of the objective functions used for the FWNS and CWNS on the environmental and economic performances were estimated using the LCA and LCC methods. The CWNS was more environmentally and economically friendly than the FWNS. Therefore, an objective function should be formulated with all of the principal contributors to the environmental burdens or economic costs and their weighting factors to synthesize the most environmentally or economically friendly water network system. The effects of the objective functions on the tradeoffs among the contributors to the environmental burdens and economic costs were also shown in the results of the LCA and LCC. The results of this study can also be applied to the process integration technologies used to generate environmentally or economically friendly heat and hydrogen network systems, because heat network synthesis uses high-, medium- and low-pressure steam as heat sources and hydrogen network synthesis utilizes high- and low-grade hydrogen gas as hydrogen sources.

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