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Positive and negative effects of excessive water reuse to be considered in water network synthesis

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Abstract−Water network synthesis has focused on maximizing water reuse to minimize freshwater consumption, even though the adverse effect of water use has not been examined until now. This study evaluates and analyzes the positive and negative effects of excessive water reuse on the environmental and economic performance of a water network system. Life cycle assessment and life cycle costing are used to evaluate the environmental impacts and economic costs of the three water systems with the different levels of water reuse. Networking for low water reuse enhances both environmental and economic performance of a water system. However, networking for excessive water reuse deteriorates the economic performance of the water system, even though this networking enhances its environmental performance. Therefore, the positive and negative effects of excessive water reuse should be taken into account in developing new pinch analysis methodologies and mathematical optimization models for water network synthesis.

Key words: Environmental and Economic Performance, Life Cycle Assessment, Life Cycle Costing, Water Network Synthesis, Water Reuse

INTRODUCTION

As cleaner production is increasingly required in line with sustainable development, much effort has been made to simultaneously reduce environmental impacts and economic costs in industrial plants. The environmental performance of systems and processes has become more important together with their economic performance in the field of process and system design. Many companies have tried to apply the concept of eco-design to their processes, systems, utilities, products and services, in order to enhance their environmental and economic performance.

Water network synthesis has been regarded as the eco-design of a water supply system in industrial plants. Water is one of the main targets of eco-design, because it is an essential resource for washing, cleaning and cooling, as well as being a product in itself, and because much environmental impacts and economic costs are incurred in water treatment, water supply and wastewater treatment. The first attempt for a water network system (WNS) was made in a petroleum refinery plant in 1980 to reduce freshwater consumption and wastewater generation [1]. The concept of the synthesis is connecting water sources (e.g., wastewater) to water sinks (e.g., water-using operations) in order to reuse wastewater. Most previous studies have focused on developing the methodology to obtain optimal solutions to mathematical optimization models, such as nonlinear programming (NLP) and mixed-integer nonlinear programming (MINLP), because of the nonconvexities derived from bilinear variables in the mass balances of contaminants [2-6]. A genetic algorithm was applied to search global optima to the MINLP model for wastewater minimization [7]. Pinch analysis has been used for water network synthesis. This analysis is to graphically find the minimum freshwater flowrate required for operating the WNS and to heuristically network water sources and sinks [8-12].

Life cycle assessment (LCA) and life cycle costing (LCC) have been used for water network synthesis. Multi-objective optimization has been studied to minimize a total annualized cost and environmental impacts of a WNS [13,14]. LCC has been employed to evaluate the economic feasibility and profitability of the WNS generated by minimizing the total flowrate of freshwater and to show the tradeoffs among economic costs incurred in the life cycle of the WNS [15]. LCA and LCC have been used to analyze principal contributors to the environmental and economic burdens of a WNS [16], and to estimate the effects of objective functions on environmental and economic performance of a WNS [17]. Mathematical optimization models have been developed to synthesize environmentally or economically friendly WNSs [18,19]. All these previous studies have shown that water reuse in water network synthesis always generates positive effects, i.e., environmental and economic benefits.

Until now, the negative effect of water reuse has not been issued and taken into account in water network synthesis. Many mathematical optimization models and pinch analysis have focused on perfectly following the fundamental concept of water network synthesis without taking into account the adverse effect of water reuse on the environmental and economic performance of a WNS. In other words, new methodologies for obtaining global optima to the model and new graphical analyses have been developed to maximize the flowrate of reused water and finally minimize the flowrate of freshwater. However, maximizing water reuse requires more intercon-

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Table 1. Limiting process data for the water network synthesis. Data source [15]

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	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	30	500	3.5	38.8	40	90
	SS	2	50	0.3			
	Cl^-	50	750	6.2			
OP 4	CODcr	20	250	2.3	36.6	40	90
	SS	3	50	0.4			
	Cl^-	20	300	3.0			
OP 5	CODcr	20	300	2.8	25.3	30	80
	SS	4	60	0.5			
	Cl^-	20	300	2.8			
OP 6	CODcr	23	400	3.2	8.3	10	70
	SS	5	80	0.6			
	Cl^-	10	200	1.5			
OP 7	CODcr	30	250	3.8	24.3	40	200
	SS	20	100	2.0			
	Cl^-	1	10	0.1			
OP 8	CODcr	10	160	1.5	8.8	10	60
	SS	2	25	0.2			
	Cl^-	1	5	0.0			
OP 9	CODcr	30	250	3.4	3.1	10	60
	SS	1	50	0.6			
	Cl^-	80	750	11.5			
OP 10	CODcr	30	300	4.5	0.8	10	40
	SS	5	15	0.1			
	Cl^-	3	40	0.4			

nections between water sources and sinks and more electricity consumption for pumping reused water from sources to sinks to decrease freshwater consumption. Therefore, the net effects of water reuse on the environmental and economic performance of a WNS should be evaluated and analyzed to obtain the insight required for synthesizing the most optimal WNS.

The objective of this study is to evaluate and analyze the positive and negative effects of excessive water reuse on the environmental and economic performance of a WNS. The environmental impacts and economic costs of three water systems are evaluated and compared to one another: (1) a conventional water system (CWS) with no water reuse; (2) an original WNS with the high flowrate of reused water; and (3) a simplified WNS with the lower flowrate of reused water than that of the original WNS. The CWS was the existing water supply system used in the plant. The original WNS was generated from the optimal solution to a mathematical optimization model, and the simplified WNS was obtained by eliminating interconnections with a low flowrate from the original WNS. The three systems were specifically designed on the same design criteria to obtain data needed for environmental and economic evaluation. Their environmental and economic performance is evaluated by using LCA and LCC. The effects of the flowrate of reused water on the tradeoffs between the environmental and economic performance of a WNS are analyzed from the results of the LCA and LCC.

METHODS

Ten water-using operations in an iron and steel industry were selected as water sources and sinks for water network synthesis. These operations are used for steelmaking, continuous casting, cold forming, and electroplating processes. Their limiting process data used for the water network synthesis are presented in Table 1. The capacities and concentrations of freshwater sources are shown in Table 2.

1. Water Network Synthesis

The original WNS was synthesized based on the superstructure

Table 2. Capacities and concentrations of freshwater sources. Data source [15]

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

Table 3. Pipe lengths between water sources and sinks. Data source [15]

	FW1	FW2	OP1	OP2	OP3	OP4	OP5	OP6	OP7	OP8	OP9	OP10
OP1	2250	280										
OP2	2060	1010	1010									
OP3	4960	4930	4980	4980								
OP4	2090	410	460	280	4140							
OP5	920	1010	1030	140	4120	650						
OP6	980	1140	1200	220	4060	710	170					
OP7	4550	4580	4660	4390	380	4280	3900	3850				
OP8	4600	4660	4710	4470	410	4330	4010	3960	220			
OP9	2710	2490	2550	2280	2440	2440	1790	1740	1930	1900		
OP10	2850	2580	2600	2300	2550	2580	1820	1760	1870	1840	140	
TP1			460	520	4880	300	520	570	4660	4740	2820	2930
TP2			4770	4500	460	4390	4010	3960	300	330	2060	2120
TP3			4820	4580	410	4440	4120	4060	330	280	2030	1980
TP4			2680	2410	2200	2580	1930	1870	2090	2060	300	350
TP5			2630	2360	2250	2530	1880	1820	2140	2110	350	300

FW: Freshwater, OP: Water-using operation, TP: Local wastewater treatment plant, Unit: meter

model presented by Lim et al. [15] This model includes all possible interconnections from the outlet of one operation to the inlets of the other operations, as well as between freshwater sources and operations, in order to increase water reuse and decrease freshwater consumption. However, the model does not include the local recycling that returns the effluent of an operation into the influent of the same operation because the local recycling requires too high pumping flowrate. Freshwater sources are not directly connected to local wastewater treatment plants, in order to prevent the loss of freshwater.

The original WNS was generated from the optimal solution to the mathematical optimization model presented by Lim and Park [16]. The objective function was to minimize the total cost of freshwater used in a water system. GAMS/MINOS [20] was used as an NLP solver to obtain the optimal solution.

The simplified WNS was generated by eliminating the interconnections with a low flowrate of less than 4.0 m^3/h in the original WNS. The reused water through the eliminated interconnection was replaced with freshwater with the same flowrate. Hence, the flowrate of reused water in the simplified WNS was less than that in the original WNS.

2. Water System Design

The three water systems were designed as a preparatory step for performing LCA and LCC. The existing water system in the plant was redesigned to obtain the CWS, which was performed on the basis of the same design criteria and assumptions as those applied to the original and simplified WNSs in order for impartially comparing the environmental and economic performance of the three water systems.

The pipe diameter and head loss were calculated simultaneously with the flowrate and pipe length. The head loss was calculated using the Darcy-Weisbach equation [21]. The maximum head loss criteria were employed for the selection of the nominal pipe diameter and were set at 200 and 20 kPa for pumping and gravity flows, respectively. Carbon steel was selected as the pipe material. The Korean Standard, KS D3507, was used to obtain specific data, such as the nominal diameter, wall thickness and weight [22]. The minimum nominal pipe diameter was set at 0.025 m for the sake of simplicity of the design. The pipe lengths between the water sources and sinks are presented in the distance matrix (Table 3).

The pumps and electric motors were specified 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 operations. The water pressures required at the end of the pipe were assumed to be 250 and 100 kPa for operations and local wastewater treatment plants, respectively. The streams of wastewater were combined and connected to local wastewater treatments.

Pump pits were designed to take into account the storage of wastewater, which was required for pumping wastewater to operations for water reuse and to local wastewater treatment plants. The hydraulic retention time of the pump pits was set at 30 min.

3. Life Cycle Assessment

LCA was performed to evaluate the environmental impacts associated with each water system. All the impacts from inputs and outputs throughout the life cycle were assessed on the basis of the design results. The LCA procedure was performed in accordance with the ISO 14040 series of standards [23]: 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 system, function, functional unit, reference flow, system boundaries, allocation, data qualities and assumptions. The goal of this LCA was to evaluate and analyze the effect of water reuse on the environmental performance of a WNS. The system and its function were defined as each water system designed to supply water-using operations with industrial and deionized water and to transfer wastewater to local wastewater treatment plants. The functional unit was defined as a water system needed for the ten operations during its life cycle, and the reference flow was set to one unit of the water system. The system boundaries included all the items in the water system, with the exception of 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 discharges of contaminants from the three water systems were the same. The allocation was not required in this LCA. The same data qualities were used for the comparative assessment, because the data were calculated from the same design criteria and assumptions. The service life of the three water systems was assumed to be 15 years with respect to the lifetime of pipes and mechanical equipment.

LCI was performed to quantify all the inputs and outputs associated with each water system in the construction, operations and maintenance (O&M) and disposal stages. The GaBi 4.0 [24] and Ecoinvent v1.2 [25] databases were used for the LCI. The inventory included (1) the manufacture of pipes, pumps and motors, the construction of pump pits, transportation, and piping works in the construction stage; (2) the consumption of industrial and deionized water and electricity in the O&M stage; and (3) the recycling of steel, iron and copper, and the landfill of concrete in the disposal stage.

LCIA was performed to evaluate the significance of potential environmental impacts on the basis of the LCI results. The CML 2001 methodology was used for the classification and characterization [24]. The extent of environmental impacts was expressed as the value of the environmental effect score (EES). The environmental impact categories are as follows: abiotic depletion potential; acidification potential; eutrophication potential; global warming potential; freshwater and marine aquatic ecotoxicity potential; human toxicity potential; terrestrial ecotoxicity potential; and photochemical ozone creation potential.

The life cycle interpretation was performed to comprehensively analyze the effect of water reuse on the environmental performance of a WNS. The EESs of the three systems were compared in order to examine the variation of the environmental performance of a WNS with reference to the flowrate of reused water.

4. Life Cycle Costing

LCC was employed to evaluate the economic costs associated with each water system. The LCC in this study focused on the cost estimation related to traditional management accounting, even though the intangible and external costs needed to be estimated for environmental accounting methods, such as full cost accounting (FCA) and total cost assessment (TCA) [26,27].

The life cycle stages of the LCC were divided into four categories: design and supervision, construction, O&M and disposal. The detailed costs are as follows: (1) costs for basic and detailed designs and supervision in the design and supervision stage; (2) costs for piping, equipment and pump pits, construction expenses, and the contractor's overhead and profit in the construction stage; (3) operating costs for industrial and deionized water and for electricity, and maintenance and repairs (M&R) costs in the O&M stage; and (4) costs for decommissioning, recycling and landfill, construction expenses, and the contractor's overhead and profit in the disposal stage. These costs were estimated in detail using databases consisting of price and cost information [28,29]. The service life for the LCC was set at 15 years, as in the case of the LCA.

The future costs were discounted to the present values to take into account the time value of money and then the present values were summed to obtain the life cycle cost of each water system. The O&M cost recurs annually, and the disposal cost is incurred at the end of the service life. Hence, the costs in the O&M and disposal stages should be converted to the present values in order to be equally compared to the initial capital investment cost [30]. The present value was estimated by using the following equation:

$$PV=P(1+e)^y/(1+i)^y \quad (1)$$

where PV=present value; P=future value; e=escalation rate; i=dis-

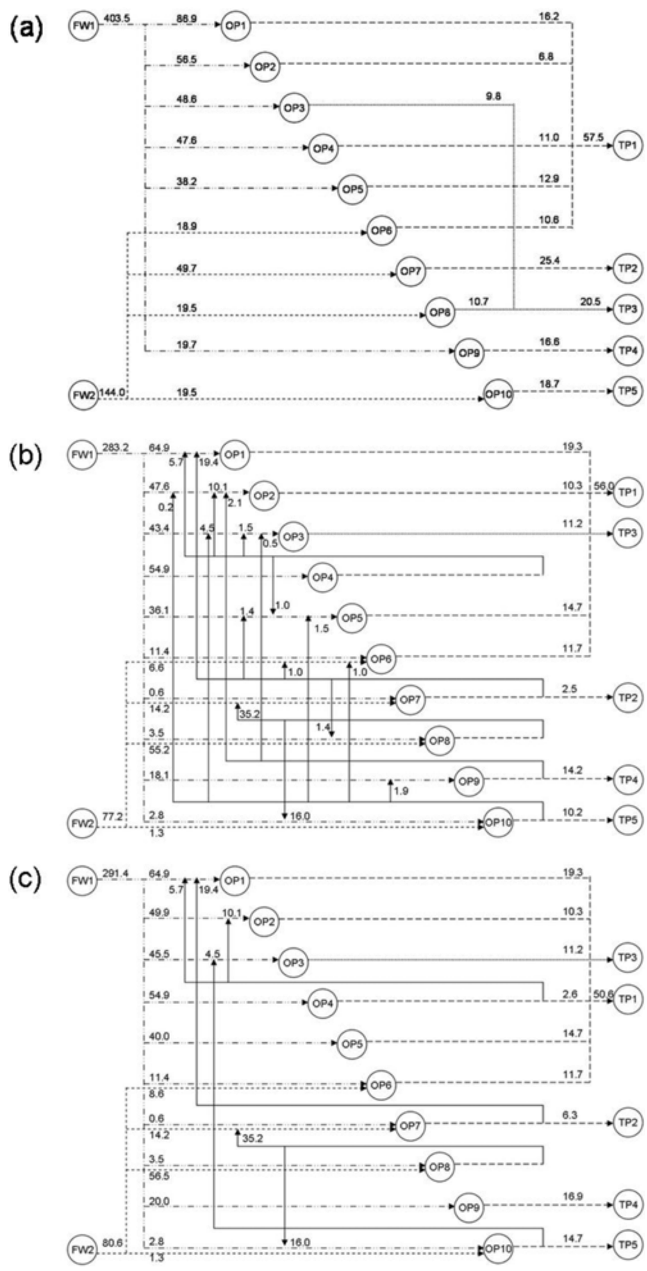

Fig. 1. Configurations of the three water systems: (a) CWS; (b) original WNS; (c) simplified WNS. Fig. 1(a) is derived from the existing water supply system based on the data in Table 1 (data source: [15]). Fig. 1(b) is generated in this study by minimizing the total cost of freshwater. Fig. 1(c) is generated by eliminating the interconnections with a low flowrate of less than 4.0 m^3/h in the original WNS (FW: Freshwater, OP: Water-using operation, TP: Local wastewater treatment plant, Unit: m^3/h).

count rate; t=time. The interest rate was set at 5.7% in relation to the yields of treasury bonds (5-years) over the last 10 years in South Korea [31], and the escalation rate was assumed to be the 3.0% targeted by the Bank of Korea for the period between 2004 and 2006 [32]. The life cycle costs of the three water systems were compared to examine the variation of the economic performance of a WNS and the tradeoffs between the environmental and economic performance of a WNS with reference to the flowrate of reused water.

RESULTS AND DISCUSSION

The configurations of the three water systems are shown in Fig. 1. The CWS (Fig. 1(a)) did not have the interconnections used for water reuse, as in the existing water supply system in the plant. The original WNS (Fig. 1(b)) had the most complicated configuration because of the seventeen interconnections needed to maximize the opportunities of water reuse. The simplified WNS (Fig. 1(c)) had the six interconnections with a high flowrate because the interconnections with a low flowrate less than 4.0 m^3/h in the original WNS were eliminated to obtain the simplified WNS. The advantages and disadvantages of the three water systems are summarized in Table 4.

The water network synthesis decreased the rates of utility consumption and wastewater generation, but increased the length and weight of pipes, as well as the volume of pump pits, as summarized in the design results of the CWS and original WNS (Table 5). The total freshwater consumption rate of the original WNS was 34.2% less than that of the CWS, which shows that the water network synthesis contributed to the conservation of water resources. The decrease ratio of the consumption of deionized water was greater than that of industrial water: the flowrate of deionized water was decreased by 46.4%, while that of industrial water was decreased by 29.8%. This was because the objective function of the mathematical optimization model drove the consumption of industrial water rather than of deionized water to minimize the total freshwater cost: the unit cost of industrial water (USD 0.60 per m^3) was less than that of deionized water (USD 0.85 per m^3). The total wastewater generation rate was reduced by 66.6%, which was in line with the decrease in the consumption of freshwater. This could reduce the operating costs and enhance the removal efficiency of wastewater treatment plants because of the decrease of hydraulic loads. The power requirement for pumping in the original WNS was 7.8% less than that in the CWS because of the decrease in freshwater consumption and wastewater generation. The total length and weight of the pipes in the original WNS were 143.4% and 20.1% greater than those in the CWS, respectively, because of the interconnections for water reuse. The total volume of pump pits in the original WNS was 29.8% less than that in the CWS because the decrease of the wastewater generation rate outweighed the increase of the flowrate of reused water. Therefore, the tradeoffs between the pipes and the other items were incurred through the water network synthesis.

The simplification of the original WNS increased the rates of the freshwater consumption and wastewater generation, but decreased the electricity consumption rate, the length and weight of the pipes, and the volume of pump pits. The design results of the original and simplified WNSs are summarized in Table 5. The total freshwater flowrate increased by 3.2% as a result of the simplification: the flowrates of industrial and deionized water increased by 2.9% and 4.4%, respectively. The wastewater generation rate also increased by 14.5%, because the increase of the freshwater consumption rate induced the increase of the wastewater generation rate to compensate for the decrease of the flowrate of reused water. The power requirement for pumping in the simplified WNS was 3.9% less than that

Table 4. Advantages and disadvantages of the three water systems

	CWS	Original WNS	Simplified WNS
Advantage	- Simplest system configuration due to no water reuse	- Lowest consumption and generation of freshwater and wastewater, respectively, due to the highest water reuse	- Relatively low consumption and generation of freshwater and wastewater, respectively, due to the effective water reuse - Relatively simple system configuration due to select interconnections for effective water reuse
Disadvantage	- Highest consumption and generation of freshwater and wastewater, respectively	- Most complicated system configuration due to many interconnections, pumps, etc., for maximization of water reuse	-

Table 5. Summary of the design results for the three water systems

Item		Unit	CWS	Original WNS	Simplified WNS
Pipe	Length	m	32,010	77,920	54,720
	Weight	kg	738,627	887,190	804,238
Pump pit	Volume	m^3	141	99	96
Utility consumption	Industrial water	m^3/hr	403.5	283.2	291.4
	Deionized water	m^3/hr	144.0	77.2	80.6
	Electricity	kW	130.2	120.0	115.3

Table 6. Results of the life cycle impact assessment for the three water systems throughout the life cycle. The CML 2001 methodology was employed for the classification and characterization

	Construction (A)			O&M (B)			Disposal (C)			The life cycle (A+B+C)		
	CWS	Original WNS	Simplified WNS	CWS	Original WNS	Simplified WNS	CWS	Original WNS	Simplified WNS	CWS	Original WNS	Simplified WNS
ADP	1.50E+03	1.99E+03	1.80E+03	2.03E+05	1.92E+05	1.93E+05	5.43E+03	6.52E+03	5.91E+03	2.10E+05	2.00E+05	2.01E+05
AP	8.05E+02	1.07E+03	9.77E+02	1.52E+05	1.34E+05	1.38E+05	2.51E+03	3.01E+03	2.73E+03	1.55E+05	1.38E+05	1.41E+05
EP	1.81E+02	2.45E+02	2.24E+02	2.31E+04	2.03E+04	2.09E+04	2.06E+02	2.46E+02	2.23E+02	2.35E+04	2.08E+04	2.13E+04
FAETP	9.74E+04	1.29E+05	1.17E+05	5.45E+06	4.94E+06	5.03E+06	1.58E+05	1.62E+05	1.53E+05	5.71E+06	5.23E+06	5.30E+06
GWP	1.92E+05	2.56E+05	2.33E+05	3.88E+07	3.59E+07	3.63E+07	5.76E+05	6.91E+05	6.27E+05	3.95E+07	3.68E+07	3.71E+07
HTP	6.24E+05	8.26E+05	7.49E+05	2.38E+07	2.15E+07	2.19E+07	3.53E+05	4.24E+05	3.84E+05	2.48E+07	2.27E+07	2.30E+07
MAETP	1.15E+08	1.52E+08	1.38E+08	1.85E+10	1.72E+10	1.74E+10	1.90E+08	2.22E+08	2.03E+08	1.88E+10	1.75E+10	1.77E+10
POCP	2.12E+02	2.82E+02	2.56E+02	1.48E+04	1.32E+04	1.35E+04	3.78E+02	4.54E+02	4.12E+02	1.54E+04	1.39E+04	1.42E+04
TETP	1.49E+03	1.98E+03	1.79E+03	4.41E+05	4.08E+05	4.11E+05	1.86E+02	2.23E+02	2.02E+02	4.43E+05	4.10E+05	4.13E+05

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

in the original WNS. This was because the interconnections with a low flowrate required high head losses due to their long lengths and because the efficiencies of their pumps and electric motors were lower than those for pumping at higher rates, even though the total flowrate of freshwater increased by 3.2% in the simplified WNS. The total length and weight of the pipes in the simplified WNS were 29.8% and 9.3% less than those in the original WNS, respectively, because the interconnections with a low flowrate were eliminated. The total volume of pump pits in the simplified WNS was 3.0% less than that of in the original WNS, because the decrease of the flowrate of reused water outweighed the increase of the rate of wastewater generation. Therefore, the simplification induced the tradeoffs between the increase of the rates of freshwater consumption and wastewater generation and the decrease of the quantities of the other items.

The synthesis decreased environmental impacts throughout the life cycle, but the simplification increased when the LCA results of the three water systems were compared to one another. Table 6 shows the EESs of each water system as the LCIA results. As a result of the synthesis, the EESs in the construction and disposal stages of the original WNS were greater than those of the CWS, but the EESs in the O&M stage of the original WNS were less. This was because water reuse required the interconnections from water sources to sinks and reduced freshwater consumption rate. The EESs during the life cycle of the original WNS were 6.5% to 11.3% less than those of the CWS because the decrease of the EESs in the O&M stage outweighed the increase of the EESs in the construction and disposal stages. As a result of the simplification, the EESs in the construction and disposal stages of the simplified WNS were less than those of the original WNS, but the EESs in the O&M stage of the simplified WNS were greater, because the interconnections with a low flowrate in the original WNS were eliminated and because the freshwater consumption rate increased to compensate for the reused water utilized through the eliminated interconnections. The EESs during the life cycle of the simplified WNS were 0.4% to 2.4% greater

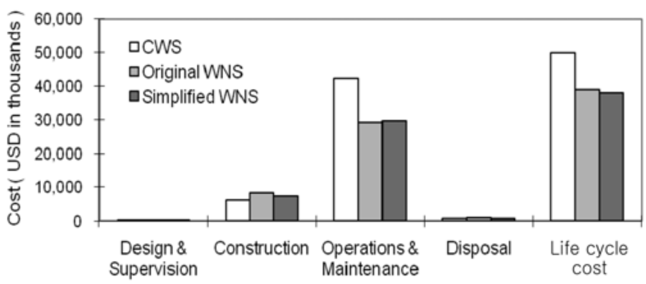

Fig. 2. Cost estimates in each life cycle stage and life cycle costs. Future costs were discounted to present values.

than those of the original WNS because the increase of the EESs in the O&M stage outweighed the decrease of the EESs in the construction and disposal stages. Therefore, the original WNS was the most environmentally friendly among the three water systems, even though the original WNS had complexities derived from the interconnections with a low flowrate.

The synthesis and simplification reduced economic costs during the life cycle when the LCC results of the three water systems were compared to one another. Fig. 2 shows the economic costs of each water system throughout the life cycle. As a result of the synthesis, the economic costs in the design and supervision, construction, and disposal stages of the original WNS were greater than those of the CWS, but the economic cost in the O&M stage of the original WNS was less. This was because the interconnections for water reuse were generated from the water network synthesis in order to reduce freshwater consumption rate. The life cycle cost of the original WNS was 21.7% less than that of the CWS because the decrease of the economic costs in the O&M stage outweighed the increase of the economic costs in the construction and disposal stages. As a result of the simplification, the economic costs in the design and supervision, construction, and disposal stages of the simplified WNS were less than those of the original WNS but the economic costs in the

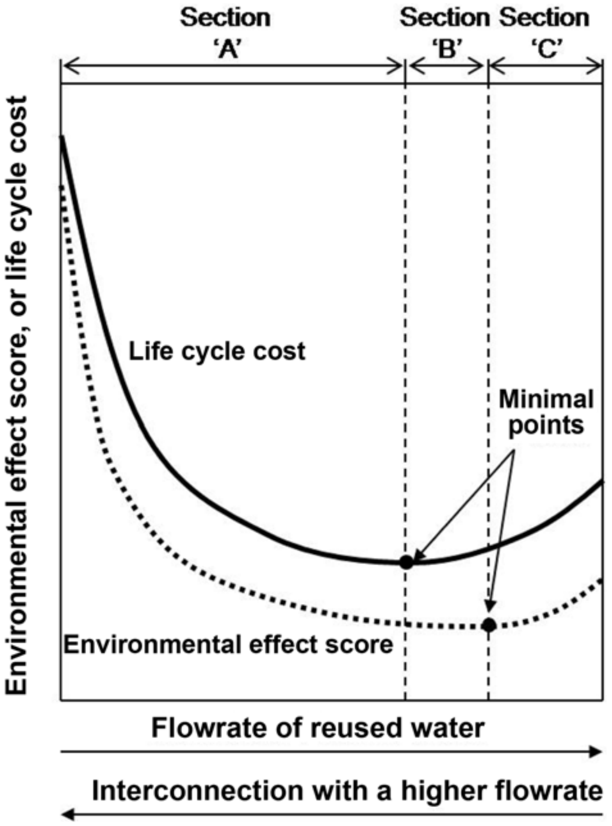

Fig. 3. Schematic variations of the environmental effect score (EES) throughout the life cycle and the life cycle cost with reference to the flowrate of reused water in water network synthesis.

O&M stage of the simplified WNS were greater, as in the LCA results mentioned above. However, the life cycle cost of the simplified WNS was 2.1% less than that of the original WNS, even though the EESs of the simplified WNS were greater than those of the original WNS. This was because the decrease of the economic costs in the design and supervision, construction and disposal stages outweighed the increase of the economic costs in the O&M stage. Therefore, the simplified WNS was the most economical among the three water systems.

The variations of the environmental and economic performance of a WNS were analyzed from the results of the LCA and LCC. Fig. 3 shows the schematic variations of the EES throughout the life cycle and life cycle cost with reference to the flowrate of reused water. In section 'A', the environmental and economic performance is improved together by utilizing the environmentally and economically positive effect of water reuse: the ESS and life cycle costs decreased because of the decrease in the freshwater consumption rate. In section 'B', a tradeoff between the environmental and economic performance is incurred, because the minimum values of the EES and life cycle cost occur at the different flowrates of reused water: the tradeoffs from the simplification resulted in the increase of environmental impacts and the decrease of economic costs. Therefore, the tradeoff between the environmental and economic performance should be optimized to obtain the most environmentally and economically sustainable WNS. In section 'C', the environmental and economic performance can deteriorate together because of the environmentally and economically negative effect of water reuse; for example, in case the increase of the environmental impacts from inefficient interconnections overrides the decrease of environmental impacts from the reduction of the rate of freshwater consumption, environmental impacts and economic costs can increase together.

CONCLUSIONS

The positive and negative effects of excessive water reuse on the environmental and economic performance of a WNS were analyzed from the results of the LCA and LCC on the CWS, original WNS and simplified WNS. The water network synthesis contributed to enhancing the environmental and economic performance simultaneously. However, the simplification deteriorated the environmental performance because of the environmentally adverse effect of the water reuse using inefficient interconnections with a low flowrate. The variation of the environmental and economic performance with reference to the flowrate of reused water was analyzed based on the LCA and LCC results. The results of this study suggest that future studies on water network synthesis be focused on developing the new pinch analysis methodologies and mathematical optimization models to differentiate and select efficient and effective interconnections between water sources and sinks rather than on maximizing the flowrate of reused water and minimizing freshwater consumption.

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