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ORIGINAL PAPER

Analysis of inter-plant water integration with indirect integration schemes through game theory approach: Pareto optimal solution with interventions

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Abstract Fresh resources such as water can be conserved through effective reuse/recycle among several industrial plants with inter-plant water integration (IPWI) scheme. Two types of IPWI schemes exist, i.e. direct and indirect integrations. This article focuses on the latter, where the water networks are integrated indirectly through a centralised utility hub (CUH). The CUH acts as a buffer to collect water from different networks, where water is intercepted for further reuse/recycle (regeneration) and/or for final environmental discharge. A recent developed game theory approach is extended for the use of indirect IPWI schemes in this study. Besides, intervention by an eco-industrial park (EIP) authority is included in the analysis to investigate the influence of incentive on the participation of water network in the IPWI.

Keywords Resource conservation · Indirect integration · Eco-industrial park · Game theory · Water minimisation

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List of symbols

Sets

K	$\{k \mid k$ is a network$\}$
I	$\{i \mid i$ is a process source$\}$
J	$\{j \mid j$ is a process sink$\}$
S	$\{s \mid s$ is an integration scheme$\}$

Variables

$ACS_{k,s}$	Annual cost savings for network k in scheme s
$E_{k,s}^{save}$	Wastewater cost savings for network k in scheme s
$F_{k,s}^{save}$	Fresh water savings for network k in scheme s
f_{FWk}	Minimum fresh water flowrate required in network k before implementing IPWI (base case)
f_{WWk}	Minimum wastewater flowrate generated in network k before implementing IPWI (base case)
f_{Wi}	Wastewater flowrate from source i
$f_{FWk,s}^{IPWI}$	Minimum fresh water flowrate required in network k in scheme s
$f_{WWk,s}^{IPWI}$	Minimum wastewater flowrate generated in network k in scheme s
$f_{i,s}^{R}$	Water flowrate sent from source i to the centralised regeneration unit in scheme s
$f_{i,s}^{T}$	Wastewater flowrate sent from source i to the centralised wastewater treatment unit in scheme s
$f_{REGk,s}$	Regenerated flowrate imported by network k in scheme s
G_s	Green incentive in scheme s
ΔL_k	Contaminant mass load need to be removed in network k prior discharge to the environment
$L_{k,s}^{IPWI}$	Total contaminant mass load sent from network k to the centralised treatment unit in scheme s
$\Delta L_{k,s}^{IPWI}$	Total contaminant mass load to be removed from network k by the centralised treatment unit in scheme s

$L^{R}_{k,s}$ Total contaminant mass load sent from network k to the centralised regeneration unit in scheme s
$PY^{INT}_{k,s}$ Internal payoff for network k in scheme s
PY^{EXT}_{s} External payoff for network k in scheme s
$P^{IND}_{k,s}$ Total annualised cross-plant piping cost for network k in scheme s
$P^{EXP}_{k,s}$ Export piping cost for network k in scheme s
$P^{IMP}_{k,s}$ Import piping cost for network k in scheme s
$Q^{save}_{k,s}$ Wastewater savings for network k in scheme s
$R_{k,s}$ Total water regeneration cost for network k in scheme s
x_s Fraction of wastewater generation by network k in scheme s

Binary variables

$x^{IND}_{k,s}$ Export pipeline connecting between network k and the centralised regeneration unit in scheme s
$y^{IND}_{k,s}$ Export pipeline connecting between network k and the centralised treatment unit in scheme s
$z^{IND}_{k,s}$ Import pipeline connecting between network k and the centralised regeneration unit in scheme s

Parameters

a Fractional interest rate per year
AF Annualised factor
AWH Annual working hours
C_R Outlet quality of regeneration unit
C_D Wastewater discharge concentration limit
cp_I Piping cost parameter I
cp_{II} Piping cost parameter II
C_{SRi} Limiting concentration of source i
C_{SKj} Limiting concentration of sink j
D Distance of cross-plant pipelines
E^{L}_{COST} Wastewater treatment cost per unit contaminant load removed
F_{SRi} Limiting flowrate of source i
F_{SKj} Limiting flowrate of sink j
IR Incentive rate
$N^{Networks}_{s}$ Total number of water networks in scheme s
N_{Sinks} Total number of sinks
$N_{Sources}$ Total number of sources
R^{m}_{COST} Water regeneration cost per unit contaminant load sent to the centralised regeneration unit
R^{f}_{COST} Water regeneration cost per unit flowrate imported from the centralised regeneration unit
W_{COST} Fresh water unit cost
y Number of years

Introduction

Recent studies reveal that the human consumption of earth's resources outstrips the planet's capacity to regenerate by 30% (WWF 2008). The surge of resource use intensity is rooted in the increased population growth especially in the industrialised and developing countries (IEA 2008). The OECD Environmental Outlook 2008 projected that by 2030, 3.9 billion people will live in areas under severe water stress, which is an additional of 1 billion people over those of today (OECD 2008). All these challenges urged for efficient use of resources by adopting sustainable resource management strategies. As concluded in the UNEP Year Book, efficient use of resources should be implemented (UNEP 2009). In relation to the sustainable resource management strategies, industrial symbiosis (IS) has been identified as an innovative waste management approach (UNEP 2009).

IS engages traditionally individual industries in a collective physical exchange of materials, energy, water and by-products to gain both environmental and economic benefits (Chertow 2007). As a result, industrial owners gained benefits from IS through fresh resource and waste treatment costs savings as the consumption of resources in the processes are optimised (Frosch and Gallopoulos 1989). Despite the benefits from the established inter-plant resource conservation networks (IPRCNs), the different interests exist among the plant owners often becomes the barrier for such collaboration work. Therefore, the IPRCNs need to be carefully designed to achieve a mutually beneficial cooperation among the participating plants (Chertow 2007; Schwarz and Steininger 1997; Fichtner et al. 2005).

Until recently, various process integration tools such as insight-based pinch analysis (Olesen and Polley 1996; Spriggs et al. 2004; Chew et al. 2007; Foo 2008; Bandyopadhyay et al. 2009; Chew et al. 2009a) and mathematical optimisation (Keckler and Allen 1998; Nobel and Allen 2000; Liao et al. 2007; Lovelady et al. 2007; Chew et al. 2008; Chen et al. 2009; Chew and Foo 2009; Lovelady and El-Halwagi 2009; Lovelady et al. 2009) were used to synthesise optimum IPRCNs. Although these techniques are useful in synthesising the IPRCN with overall minimum flowrates or cost, it, however, does not guarantee the maximum benefits for each participating network (in an individual basis). Nor do these methods fully reflect that these individual networks act in self-interest that may conflict with the overall goals of the IPRCN. A recent work by Chew et al. (2009b) adopted *game theory* approach to assist the selection of optimum inter-plant water integration (IPWI) scheme which guaranteed the maximum benefits for each participating water networks. In their work, alternative IPWI schemes with *direct integration* schemes (participating water networks are integrated directly through cross-plant pipelines) were analysed through *non-cooperative* and *cooperative* game approaches. In game theory perspective, a game is categorised as non-cooperative if the participants do not make binding commitments to coordinate their strategies. In contrast, a cooperative game is defined as a game in which participants make binding agreements to coordinate their strategies (Nash 1950; Nash 1951; McCain 2004; Osborne 2004). Optimum integration schemes for these approaches, i.e. *Nash equilibrium* (for non-cooperative approach) and *Pareto optimal* solutions (cooperative approach), are selected based on rational self-interest of each participant. Nash equilibrium in any non-cooperative game is a solution from which no player (i.e. individual water network) can unilaterally deviate to improve his/her payoff (Nash 1950; Nash 1951; McCain 2004; Osborne 2004). On the other hand, Pareto optimal is the best solution (refers to IPWI scheme in this case) that one can make in a cooperative game. A solution is Pareto optimal if no one can be made better off without making someone worse off (McCain 2004).

On the other hand, Aviso et al. utilised fuzzy mathematical programming in synthesising the optimum IPRCNs (Aviso et al. 2010a, b). In the fuzzy optimisation model, the upper and lower limits of the fuzzy goal for each water network are specified, and the model is solved to maximise the level of satisfaction achieved by each participating networks. The optimum solution obtained in the fuzzy optimisation is the Pareto optimal solution through cooperative game approach (Aviso et al. 2010a). Further work integrates the role of an external agent (e.g. government) in inducing cooperation among companies using economic instruments such as fees and subsidies (Aviso et al. 2010b). Other works using game theory approach in the analysis of industrial ecology are such as those in carbon emission reduction (Jørgensen and Zaccour 2001; Breton et al. 2008), emergy analysis (Lou et al. 2004), drinking water-supply system improvement (Peldschus and Zavadskas 2005), industrial ecology optimisation (Singh and Lou 2006), analysis of post-consumer beverage packaging waste (Grimes-Casey et al. 2007) and the synthesis of wastewater neutralisation network (Kim and Lee 2007).

In this study, the recent developed game theory approach for direct integration (Chew et al. 2009b) is extended for the analysis of *indirect integration*. In this scheme, water networks are interconnected via a centralised utility hub (CUH). The main advantage of such arrangement is that, it is more practical in handling large number of water networks in the IPWI scheme (Chew et al. 2008; Chen et al. 2009). Note that the CUH is commonly used in eco-industrial parks (EIPs), wherein the CUH provides shared services to multiple plants which include source interception, wastewater treatment and fresh resource supply services (Spriggs et al. 2004; Lovelady et al. 2007; Lovelady and El-Halwagi 2009; Lovelady et al. 2009). In the following section, a set of indirect integration schemes are first generated (using pinch analysis techniques). Next, the integration schemes are analysed through non-cooperative and cooperative game approaches, from which an optimum integration scheme (Nash equilibrium or Pareto optimality) is to be determined.

Problem statement

Given a set of water networks k of the fixed flowrate type problem, with process sinks j and sources i that may be considered for water reuse/recycle, where each sink and source has a limiting water flowrate and concentration. External fresh water source(s) is used to supplement additional water requirement of the process sink that is not satisfied by the process sources. All water networks share a common CUH where water regeneration and wastewater treatment facilities are made available for service. The alternative IPWI schemes are analysed using game theory approach based on two different payoffs, based on *internal* and *external* costs. The former reflects the combined capital and operating costs. In contrast, the external cost is associated with environmental damage for which conventional approaches fail to account. However, such costs may be internalised through the application of incentives (or disincentives) imposed by an authority to induce companies to act in an environmentally responsible manner. Game theory provides a rigorous framework for the analysis of such mechanisms, which in practice may be in the form of taxes, pollution fees, subsidies, etc. (Salman and Cruz 1981; Ho et al. 1982; Cruz and Simaan 1999). In this study, the intervention of the EIP authority in the cooperative game approach by providing *green incentive* to the participating networks is analysed.

Model for payoff based on internal costs

Figure 1 shows the generic structure of an indirect integration scheme for a set of water network k. As shown, the CUH provides services to regenerate water and to treat wastewater for all networks (with service costs incurred). The effluent from each network is sent to the centralised regeneration and waste treatment units (with flowrate $f^{R}_{i,s}$ and $f^{T}_{i,s}$, respectively). The regenerated water (with flowrate of $f_{REGk,s}$) is then imported by network k as a secondary water source besides fresh water. The unused water from the network is then sent for treatment to an allowable quality (C_D) prior to environmental discharge. One may also view this as a *total water network* of multiple plants, conceptually similar to the work presented earlier (Ng et al. 2007a, b; Chew and Foo 2009).

In the following section, it is assumed that a regeneration unit of the fixed outlet quality type and a wastewater

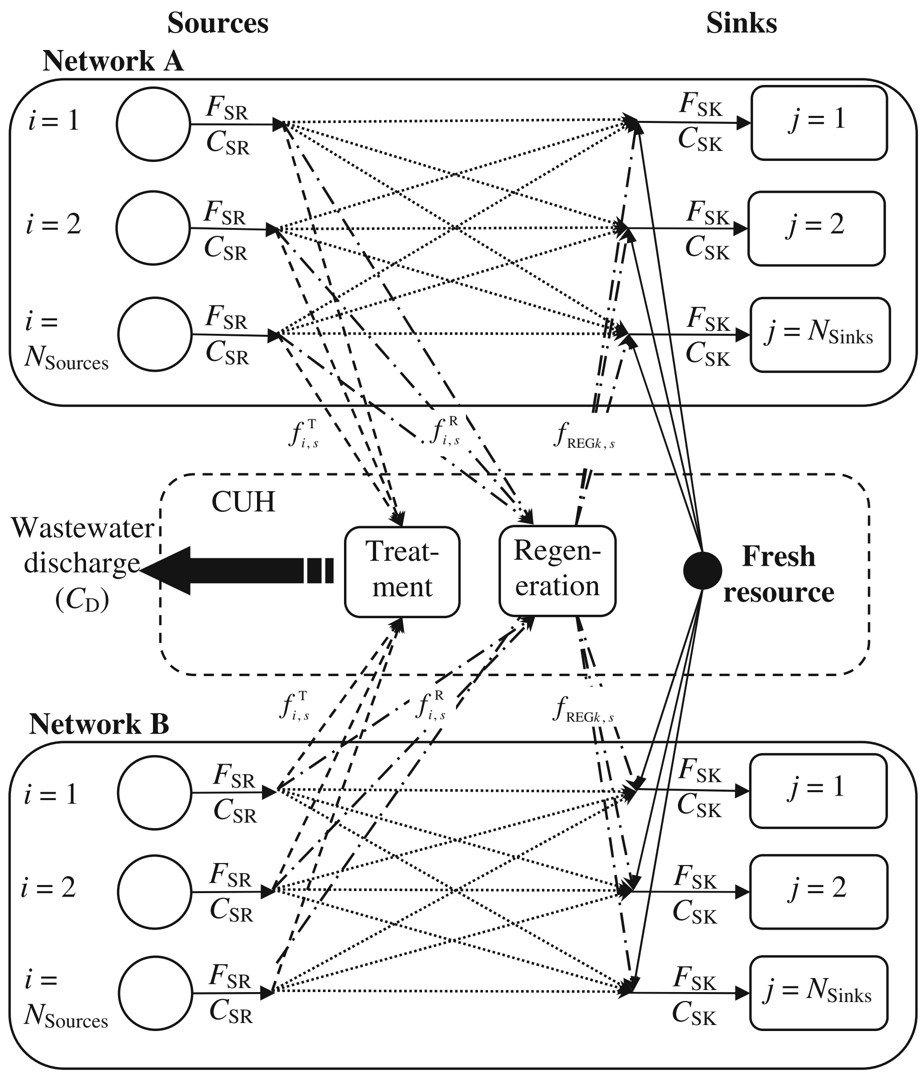

Fig. 1 Indirect integration scheme

treatment unit of the fixed removal ratio (RR) type are used. The RR is defined as the ratio of the contaminant load removed from the inlet load (Wang and Smith 1994). The internal payoff $\left(\mathrm{PY}_{k,s}^{\mathrm{INT}}\right)$ is shown in Eq. 1, which considers the annual cost savings ($\mathrm{ACS}_{k,s}$), water regeneration cost ($R_{k,s}$) and the annualised cross-plant piping cost $\left(P_{k,s}^{\mathrm{IND}}\right)$. The $\mathrm{ACS}_{k,s}$ is a result of the reduction of fresh water $\left(F_{k,s}^{\mathrm{save}}\right)$ flowrate and contaminant mass load in the wastewater treatment $\left(E_{k,s}^{\mathrm{save}}\right)$, calculated using Eqs. 2–6. In Eq. 2, AWH corresponds to the annual working hours of the water networks (assuming the same for all networks), while W_{COST} and $E_{\mathrm{COST}}^{\mathrm{L}}$ are unit cost of fresh water and contaminant load removal in the wastewater treatment, respectively. Equations 3 and 4 determine the reduction of fresh water flowrate and contaminant load upon the implementation of IPWI as compared to the base case (in-plant reuse/recycle without IPWI). Variables $f_{\mathrm{FW}k}$ and $f_{\mathrm{FW}k,s}^{\mathrm{IPWI}}$ in Eq. 3 denoted fresh water flowrate required by network k in scheme s before and after IPWI, respectively. Equation 5 denotes the total contaminant mass load removal from network k (ΔL_k) prior to environment discharge for the base case, with $f_{\mathrm{W}i}$ and $C_{\mathrm{SR}i}$ denote the wastewater flowrate from source i and its corresponding concentration. Equation 6 states the total contaminant mass load need to be removed from network k in scheme s $\left(\Delta L_{k,s}^{\mathrm{IPWI}}\right)$ by the centralised treatment unit. Variable $L_{k,s}^{\mathrm{IPWI}}$ denotes the wastewater contaminant mass load from network k in scheme s, while variable $f_{i,s}^{\mathrm{T}}$ denotes the wastewater flowrate from sources i sent to the centralised treatment unit in each integration scheme.

$$\mathrm{PY}_{k,s}^{\mathrm{INT}} = \mathrm{ACS}_{k,s} - R_{k,s} - P_{k,s}^{\mathrm{IND}} \quad \forall k \in K, \forall s \in S \tag{1}$$

$$\mathrm{ACS}_{k,s} = \left(F^{\mathrm{save}}_{k,s} W_{\mathrm{COST}} + E^{\mathrm{save}}_{k,s} E^{\mathrm{L}}_{\mathrm{COST}}\right)\mathrm{AWH} \quad \forall k \in K, \forall s \in S \tag{2}$$

$$F^{\mathrm{save}}_{k,s} = f_{\mathrm{FW}k} - f^{\mathrm{IPWI}}_{\mathrm{FW}k,s} \quad \forall k \in K, \forall s \in S \tag{3}$$

$$E^{\mathrm{save}}_{k,s} = \Delta L_k - \Delta L^{\mathrm{IPWI}}_{k,s} \quad \forall k \in K, \forall s \in S \tag{4}$$

$$\Delta L_k = \sum_{i \in I} f_{\mathrm{W}i}(C_{\mathrm{SR}i} - C_{\mathrm{D}}) \quad \forall k \in K \tag{5}$$

$$\Delta L^{\mathrm{IPWI}}_{k,s} = L^{\mathrm{IPWI}}_{k,s} - \sum_{i \in I} f^{\mathrm{T}}_{i,s} C_{\mathrm{D}} \quad \forall k \in K, \forall s \in S \tag{6}$$

The water regeneration cost ($R_{k,s}$ in Eq. 1) is determined by Eq. 7. Note that for integration scheme s, each participating network is charged by the total contaminant load sent to the centralised regeneration unit $\left(L^{\mathrm{R}}_{k,s}\right)$, as well as the minimum regenerated flowrate $\left(f_{\mathrm{REG}k,s}\right)$ imported by the participating network. Parameters $R^{\mathrm{m}}_{\mathrm{COST}}$ and $R^{\mathrm{f}}_{\mathrm{COST}}$ each denote the regeneration costs, expressed per unit of contaminant load removed and per unit of regenerated water imported, respectively. Due to the unequal regeneration flowrate sent from each network for regeneration (usually the 'cleanest' wastewater streams are selected for regeneration), the total regeneration cost $R^{\mathrm{m}}_{\mathrm{COST}}$ is allocated to the different plants based on the unit of mass load removed (instead of unit flowrate). Detailed procedure on the selection of wastewater streams for regeneration is referred to Ng et al. (2007c, 2008). Equation 8 states the total contaminant load for the combined sources being sent to the centralised regeneration unit in each scheme, with $f^{\mathrm{R}}_{i,s}$ and $C_{\mathrm{SR}i}$ denoting the water flowrate and concentration of source i, respectively.

$$R_{k,s} = \left(L^{\mathrm{R}}_{k,s} R^{\mathrm{m}}_{\mathrm{COST}} + f_{\mathrm{REG}k,s} R^{\mathrm{f}}_{\mathrm{COST}}\right)\mathrm{AWH} \quad \forall k \in K, \forall s \in S \tag{7}$$

$$L^{\mathrm{R}}_{k,s} = \sum_{i \in I} f^{\mathrm{R}}_{i,s} C_{\mathrm{SR}i} \quad \forall k \in K, \forall s \in S \tag{8}$$

The capital cost for the cross-plant pipeline ($P^{\mathrm{IND}}_{k,s}$ in Eq. 1) is adapted from Kim and Smith (2004). Equation 9 shows the total annualised cross-plant piping cost, $P^{\mathrm{IND}}_{k,s}$ for each network in scheme s, which consists of export $\left(P^{\mathrm{EXP}}_{k,s}\right)$ and import $\left(P^{\mathrm{IMP}}_{k,s}\right)$ piping costs. The former is calculated in Eq. 10, considering two export cross-plant pipings, i.e. flowrates sent from sources i to the centralised regeneration $\left(f^{\mathrm{R}}_{i,s}\right)$ and treatment $\left(f^{\mathrm{T}}_{i,s}\right)$ units. On the other hand, one import cross-plant pipeline is required to transfer the regenerated flowrate $\left(f_{\mathrm{REG}k,s}\right)$ from the centralised regeneration unit to each network, with the piping cost shown in Eq. 11. Piping capital cost within the individual network as well as that in the CUH is assumed negligible. Binary variables $x^{\mathrm{IND}}_{k,s}$ and $y^{\mathrm{IND}}_{k,s}$ in Eq. 10 indicate the presence of the export cross-plant flowrates to regeneration and treatment units, respectively; while binary variable $z^{\mathrm{IND}}_{k,s}$ in Eq. 11 indicates the presence of import cross-plant flowrate. Parameter D is the distance between the CUH and water networks k and $\mathrm{cp_I}$ and $\mathrm{cp_{II}}$ are the cross-plant pipeline cost parameters.

$$P^{\mathrm{IND}}_{k,s} = P^{\mathrm{EXP}}_{k,s} + P^{\mathrm{IMP}}_{k,s} \quad \forall k \in K, \forall s \in S \tag{9}$$

$$\begin{aligned} P^{\mathrm{EXP}}_{k,s} = D\Bigg[&\left(\mathrm{cp_I} \sum_{i \in I}\left(\frac{f^{\mathrm{R}}_{i,s}}{3600\rho v} + \mathrm{cp_{II}} x^{\mathrm{IND}}_{k,s}\right)\right) \\ &+ \left(\mathrm{cp_I} \sum_{i \in I}\left(\frac{f^{\mathrm{T}}_{i,s}}{3600\rho v} + \mathrm{cp_{II}} y^{\mathrm{IND}}_{k,s}\right)\right)\Bigg]\mathrm{AF} \\ &\forall k \in K, \forall s \in S \end{aligned} \tag{10}$$

$$P^{\mathrm{IMP}}_{k,s} = D\left(\mathrm{cp_I}\frac{f_{\mathrm{REG}k,s}}{3600\rho v} + \mathrm{cp_{II}} z^{\mathrm{IND}}_{k,s}\right)\mathrm{AF} \quad \forall k \in K, \forall s \in S \tag{11}$$

An annualising factor (AF) is used to annualise the piping capital cost in Eqs. 10 and 11, defined as (Smith 2005):

$$\mathrm{AF} = \frac{a(1+a)^y}{(1+a)^y - 1} \tag{12}$$

where a is the fractional interest rate per year and y is the number of years.

Model for payoff based on external costs

The payoff based on external costs is defined as the overall reduction of fresh water and wastewater flowrates upon the implementation of IPWI. These flowrates are assumed to provide an indication of environmental impacts through resource depletion and pollution, respectively. As shown in Eq. 13, the external payoff $\left(\mathrm{PY}^{\mathrm{EXT}}_s\right)$ used here is the summation of the overall fresh water $\left(F^{\mathrm{save}}_{k,s}\right)$ and wastewater $\left(Q^{\mathrm{save}}_{k,s}\right)$ flowrates reduction, given as in Eqs. 3 and 14, respectively. An IPWI scheme with a higher overall flowrates reduction indicates higher external payoff, as it is more environmental friendly.

$$\mathrm{PY}^{\mathrm{EXT}}_s = \sum_{k \in K} F^{\mathrm{save}}_{k,s} + \sum_{k \in K} Q^{\mathrm{save}}_{k,s} \tag{13}$$

$$Q^{\mathrm{save}}_{k,s} = f_{\mathrm{WW}k} - f^{\mathrm{IPWI}}_{\mathrm{WW}k,s} \tag{14}$$

Note that Eq. 13 assumes that fresh water and wastewater reductions are of equal importance. If necessary, the payoff function may be modified to account for weights based on the concept of water footprint (Hoekstra 2009). Alternatively, weights may be used to directly convert the flowrates into monetary equivalents.

Illustrative example

This example illustrates an indirect integration scheme that involves four water networks, taken from Wang and Smith (1994), Polley and Polley (2000), Sorin and Bédard (1999) and Wang and Smith (1995). The example is used to elucidate game theory approach in the analysis of indirect integration scheme, with its limiting water data tabulated in Table 1.

Table 2 shows the minimum fresh water (f_{FWk}) and wastewater (f_{WWk}) flowrates for each network in the base case. These flowrates can be determined using any developed pinch targeting tools such as material recovery pinch diagram (El-Halwagi et al. 2003; Prakash and Shenoy 2005), water cascade analysis (Manan et al. 2004; Foo et al. 2006), material surplus composite curve (Saw et al. 2009), etc. When no IPWI is performed, de-centralised wastewater treatment unit (RR = 0.9) is used, operated by network k. The fourth column in Table 2 summarises the individual wastewater streams identified through the waste stream identification technique of Ng et al. (2007a, b). Equation 5 is used to calculate the contaminant load removed in the decentralised wastewater treatment unit (ΔL_k), with results shown in the last column of Table 2. Note that in the base case, water regeneration is not considered.

In this example, game theoretic analysis is carried out for five indirect integration schemes, assuming that each network is operated by different business entities. Each participating water network will seek for maximum benefits based on the internal and external payoffs. The following assumptions are made in the calculation of internal and external payoffs:

1. Equal distance of $D = 200$ m between all water networks and the CUH.
2. The capital cost for the cross-plant pipelines was annualised to a period of 5 years (y) with a fixed interest rate (a) of 5%. This leads to an AF (Eq. 12) of 0.231.
3. The piping cost (Eqs. 10–11) considers the use of carbon steel pipes, with the cost parameters of $cp_I = 7{,}200$ and $cp_{II} = 250$ (given in USD; CE plant index = 318.3). The stream flowrate velocity (v) is assumed as 1 m s^{-1} and water density (ρ) as 1,000 kg m^{-3}.
4. AWH is assumed to be 7,920.
5. Unit cost for fresh water (W_{COST}) is assumed at \$1/t.
6. Regeneration unit of fixed outlet concentration ($C_R = 10$ ppm) is used.
7. Discharge concentration (C_D) is assumed at 30 ppm.
8. Regeneration service costs are assumed as $R^{m}_{COST} =$ \$2/kg load removed (for water that is sent to the centralised regeneration unit) and $R^{f}_{COST} =$ \$0.5/t treatment flowrate (imported from the CUH).
9. Wastewater treatment unit with RR = 0.9 is used, with its treatment cost $\left(E^{L}_{COST}\right)$ of \$2.36/kg load removed (El-Halwagi 2006).

The following calculations are then performed to obtain the payoffs for the various IPWI schemes.

Table 1 Limiting water data for illustrative example

Water network k	Sinks j	Flowrate F_{SKj} (t/h)	Concentration C_{SKj} (ppm)	Sources i	Flowrate F_{SRi} (t/h)	Concentration C_{SRi} (ppm)
A (Wang and Smith 1994)	SK1	20	0	SR1	20	100
	SK2	100	50	SR2	100	100
	SK3	40	50	SR3	40	800
	SK4	10	400	SR4	10	800
B (Polley and Polley 2000)	SK5	50	20	SR5	50	50
	SK6	100	50	SR6	100	100
	SK7	80	100	SR7	70	150
	SK8	70	200	SR8	60	250
C (Sorin and Bédard 1999)	SK9	120	0	SR9	120	100
	SK10	80	50	SR10	80	140
	SK11	80	50	SR11	140	180
	SK12	140	140	SR12	80	230
	SK13	80	170	SR13	195	250
	SK14	195	240			
D (Wang and Smith 1995)	SK15	20	0	SR14	20	100
	SK16	100	50	SR15	100	100
	SK17	40	50	SR16	40	800
	SK18	10	80			

Table 2 Minimum flowrate targets and contaminant load removal in the base case (in-plant reuse/recycle without IPWI)

Water network k	Fresh water flowrate f_{FWk} (t/h)	Wastewater flowrate f_{WWk} (t/h)	Individual wastewater streams		Contaminant load removed in treatment unit
			f_{Wi} (t/h)	C_{SRi} (ppm)	ΔL_k (kg/h)
A	90.00	90.00	44.29	100	38.30
			45.71	800	
B	70.00	50.00	25	150	8.50
			25	250	
C	200.00	120.00	35	180	23.95
			85	250	
D	92.00	82.00	42	100	33.74
			40	800	
Total	$\sum_{k \in K} f_{FWk} = 452$	$\sum_{k \in K} f_{WWk} = 342$	$\sum_{k \in K} f_{WWk} = 342$		$\sum_{k \in K} \Delta L_k = 104.49$

Minimum fresh water and regeneration flowrates

Table 3 shows five proposed indirect integration schemes that represent participation of different water networks. Scheme 1 involves the integration of four networks, while Schemes 2–5 involve the integration of three networks. Following the algebraic regeneration targeting techniques of Ng et al. (2007c, 2008), the minimum regenerated $(f_{REGk,s})$ and fresh water $\left(f^{IPWI}_{FWk,s}\right)$ flowrates required by each network in scheme s are determined and summarised in Table 3. The total regenerated water flowrate for each scheme can then be determined, as given in the last column of Table 3. Note that no regeneration flowrate is received in the network that does not participate in the integration scheme; hence its fresh water flowrate is referred to that in the base case (as shown in Table 2). For instance, Network D has a fresh water flowrate of 92 t/h since it does not participate in Scheme 2 (see Tables 2, 3).

In order to achieve the total regeneration flowrate as targeted in Table 3b, water sources are to be extracted from the individual network. These water sources are summarised in Table 4a. Based on the concentration of these sources, the total contaminant load sent to the regeneration unit $\left(L^{R}_{k,s}\right)$ from each network can be calculated using Eq. 8, with the results summarised in Table 4b. Note that the regenerated flowrate needed by an individual network does not need to be the same as its source flowrate that is sent for regeneration. For instance, Network B in Scheme 1 required minimum regenerated flowrate of 75 t/h (see Table 3), however, only 55 t/h of water flowrate is available for regeneration (see Table 4a). On the other hand, Network C sends 128.89 t/h of water flowrate to the regeneration unit (see Table 4a), even though it only requires 88.89 t/h of regenerated water (see Table 3). This means that Network C will supply additional wastewater flowrates to supplement regeneration flowrate requirement in other networks.

Wastewater treatment flowrate

Table 5a shows the individual source streams $\sum_{i \in I} f^{T}_{i,s}$ sent to the wastewater treatment unit. The total wastewater contaminant load removed in the wastewater treatment unit $\left(\Delta L^{IPWI}_{k,s}\right)$ can be calculated using Eq. 6, with the results summarised in Table 5b. As in the case of regeneration, a network that does not participate in the integration scheme will keep its wastewater treatment flowrate and contaminant load the same as in the base case (Table 2).

Table 3 Minimum fresh and regenerated water flowrates

Integration scheme s	(a) Fresh water flowrate $f^{IPWI}_{FWk,s}$ (t/h)					(b) Regenerated flowrate $f_{REGk,s}$ (t/h)				
	$k = A$	$k = B$	$k = C$	$k = D$	$\sum_{k \in K} f^{IPWI}_{FWk,s}$	$k = A$	$k = B$	$k = C$	$k = D$	$\sum_{k \in K} f_{REGk,s}$
1. (Networks A, B, C, D)	20	0	120	20	160	77.78	75.00	88.89	80.00	321.67
2. (Networks A, B, C)	20	0	120	92	232	77.78	75.00	88.89	0.00	241.67
3. (Networks A, C, D)	20	70	120	20	230	77.78	0.00	88.89	80.00	246.67
4. (Networks B, C, D)	90	0	120	20	230	0.00	75.00	88.89	80.00	243.89
5. (Networks A, B, D)	20	0	200	20	240	77.78	75.00	0.00	80.00	232.78

Table 4 Flowrate and contaminant load sent to the centralised regeneration unit

Integration scheme s	Network A	Network B	Network C	Network D
(a) Water sent to regeneration unit $f^{R}_{i,s}$ (t/h)				
1. (Networks A, B, C, D)	52.06 (100)	30.00 (150)	8.89 (100)	50.00 (100)
	17.86 (800)	25.00 (250)	35.00 (180)	17.86 (800)
			85.00 (250)	
2. (Networks A, B, C)	52.06 (100)	30.00 (150)	8.89 (100)	–
	5.72 (800)	25.00 (250)	35.00 (180)	
			85.00 (250)	
3. (Networks A, C, D)	52.06 (100)	–	8.89 (100)	50.00 (100)
	7.86 (800)		35.00 (180)	7.86 (800)
			85.00 (250)	
4. (Networks B, C, D)	–	30.00 (150)	8.89 (100)	50.00 (100)
		25.00 (250)	35.00 (180)	17.86 (800)
			85.00 (250)	
5. (Networks A, B, D)	52.06 (100)	30.00 (150)	–	50.00 (100)
	37.86 (800)	25.00 (250)		37.86 (800)
(b) Total contaminant load sent to regeneration unit, $L^{R}_{k,s}$(kg/h)				
1. (Networks A, B, C, D)	19.49	10.75	28.44	19.29
2. (Networks A, B, C)	9.78	10.75	28.44	0.00
3. (Networks A, C, D)	11.49	0.00	28.44	11.29
4. (Networks B, C, D)	0.00	10.75	28.44	13.00
5. (Networks A, B, D)	35.49	10.75	0.00	35.29

Values in parenthesis indicate concentration of source i (C_{SRi}) in ppm

Table 5 Flowrate and contaminant load sent to the wastewater treatment unit

Integration scheme s	Network A	Network B	Network C	Network D	Total
(a) Wastewater flowrate sent to the wastewater treatment unit, $f^{T}_{i,s}$ (t/h)					
1. (Networks A, B, C, D)	27.86 (800)	0.00	0.00	22.14 (800)	50.00
2. (Networks A, B, C)	40.00 (800)	0.00	0.00	42.00 (100)	122.00
				40.00 (800)	
3. (Networks A, C, D)	37.86 (800)	25.00 (150)	0.00	32.14 (800)	120.00
		25.00 (250)			
4. (Networks B, C, D)	44.29 (100)	0.00	0.00	30.00 (800)	120.00
	45.1 (800)				
5. (Networks A, B, D)	7.86 (800)	0.00	35.00 (180)	2.14 (800)	130.00
			85.00 (250)		
(b) Total contaminant load removed in the wastewater treatment unit, $\Delta L^{IPWI}_{k,s}$ (kg/h)					
1. (Networks A, B, C, D)	21.45	0.00	0.00	17.05	38.50
2. (Networks A, B, C)	30.80	0.00	0.00	33.74	64.54
3. (Networks A, C, D)	29.15	8.50	0.00	24.75	62.40
4. (Networks B, C, D)	38.30	0.00	0.00	23.10	61.40
5. (Networks A, B, D)	6.05	0.00	23.95	1.65	31.65

Values in parenthesis indicate concentration of source i (C_{SRi}) in ppm

With the determination of the above flowrates, the IP-RCN for all schemes are synthesised and are shown in Fig. 2. Note that the design within the individual network is not shown for simplicity. In the next section, all integration schemes are analysed through two different approaches, i.e. non-cooperative and cooperative games.

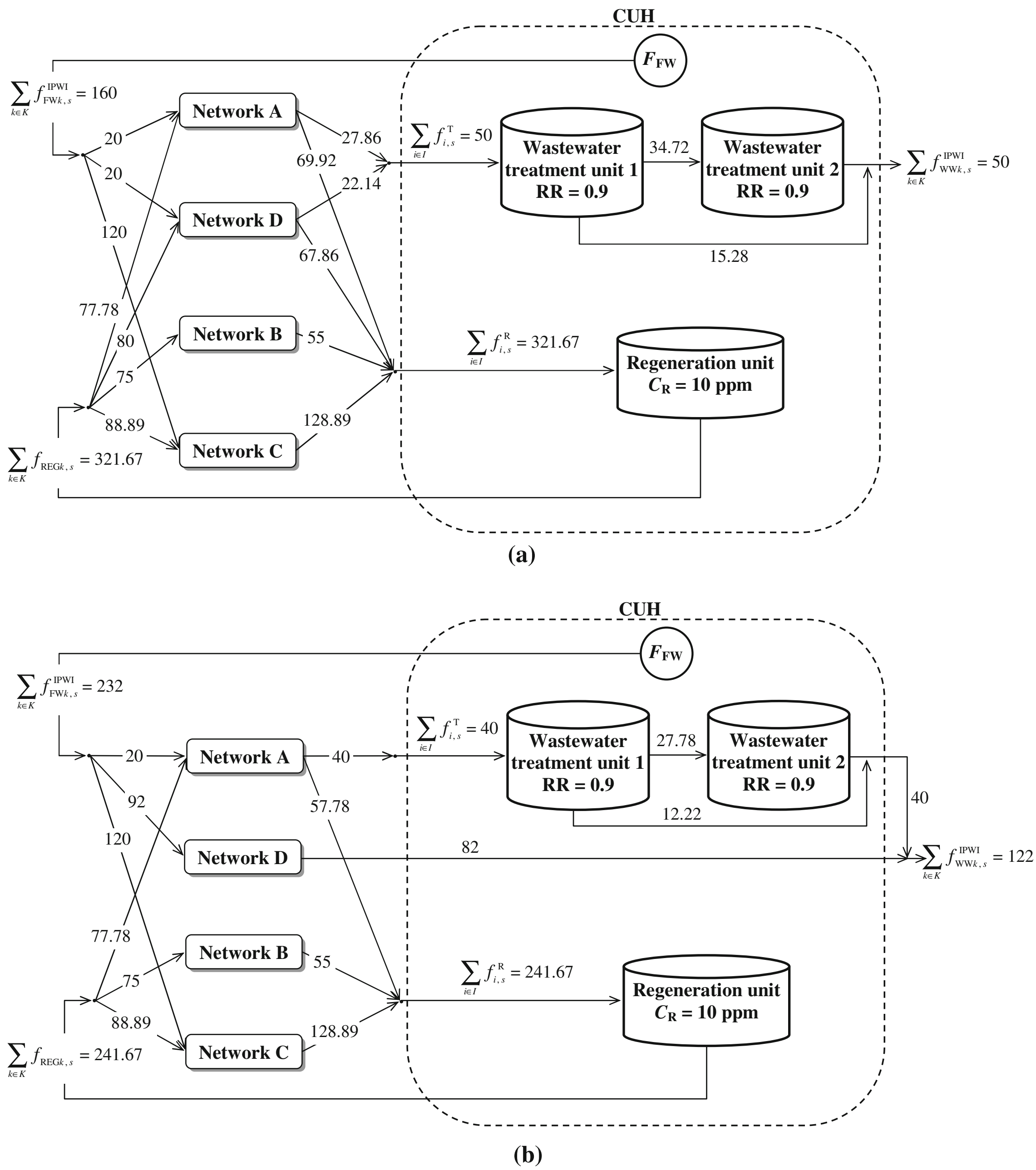

Fig. 2 Inter-plant water network design for illustrative example: **a** Scheme 1, **b** Scheme 2, **c** Scheme 3, **d** Scheme 4 and **e** Scheme 5

Finally, sensitivity analysis is carried out to check the robustness of the Nash equilibrium and Pareto optimal solutions obtained through the non-cooperative and cooperative games, respectively.

Non-cooperative game approach

In order to analyse the five integration schemes with non-cooperative game, the internal and external payoffs for each integration scheme are calculated based on the flowrates and contaminant loads determined in Tables 2, 3, 4, and 5. The results are summarised in Table 6. Note that in the last two columns of Table 6 where the external payoff is shown, the total reduction of the fresh water $\left(\sum_{k\in K} F^{save}_{k,s}\right)$ and wastewater $\left(\sum_{k\in K} Q^{save}_{k,s}\right)$ flowrates is determined using Eq. 13. For instance, Networks A, B and C participated in

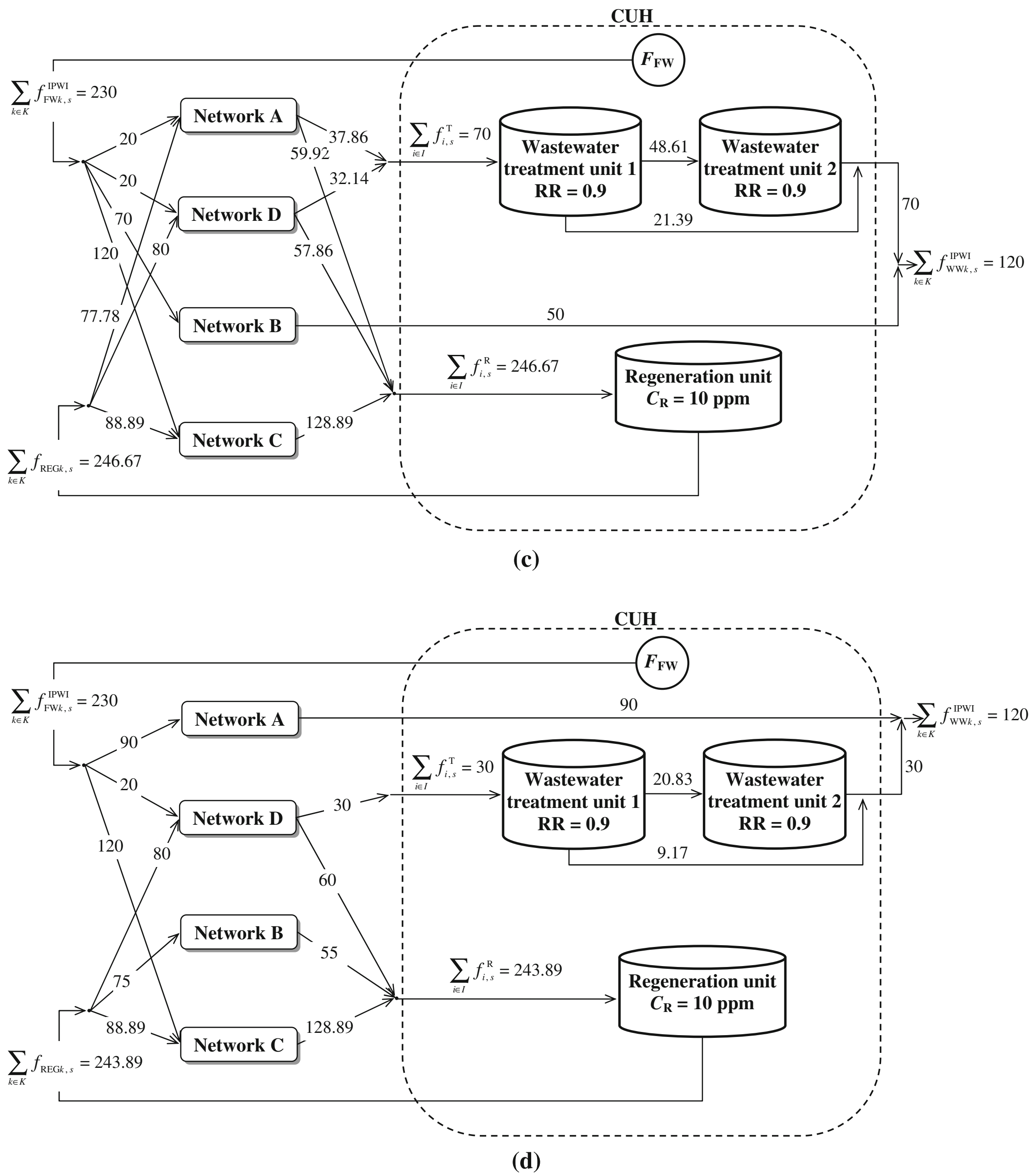

Fig. 2 continued

Scheme 2. Hence, their total fresh water flowrate $\left(\sum_{k\in K} f_{\mathrm{FW}k}\right)$ before IPWI is determined as 360 t/h (=90 + 70 + 200 t/h, see the second column of Table 2). After IPWI, the total fresh water flowrate $\left(\sum_{k\in K} f^{\mathrm{IPWI}}_{\mathrm{FW}k,s}\right)$ for this scheme is reduced to 232 t/h (see Table 3a). Therefore, the total fresh water flowrate reduction $\left(\sum_{k\in K} F^{\mathrm{save}}_{k,s}\right)$ is calculated as 128 t/h (=360 – 232 t/h). The same steps are followed to obtain the total wastewater flowrate reduction $\left(\sum_{k\in K} Q^{\mathrm{save}}_{k,s}\right)$, in which the wastewater flowrates before and after IPWI are obtained from the third column of Table 2 and the last column of Table 5a, respectively.

Analysing the payoffs in Table 6 reveals that Networks A, B and D achieve the highest individual annual internal payoff by choosing Scheme 5 ($\mathrm{PY}^{\mathrm{INT}}_{A,5} = \$236{,}129$, $\mathrm{PY}^{\mathrm{INT}}_{B,5} = \$210{,}883$, $\mathrm{PY}^{\mathrm{INT}}_{D,5} = \$243{,}960$), while Scheme 1 gives the highest external payoff $\left(\mathrm{PY}^{\mathrm{EXT}}_{1} = 292 + 292 \text{ t/h}\right)$. This

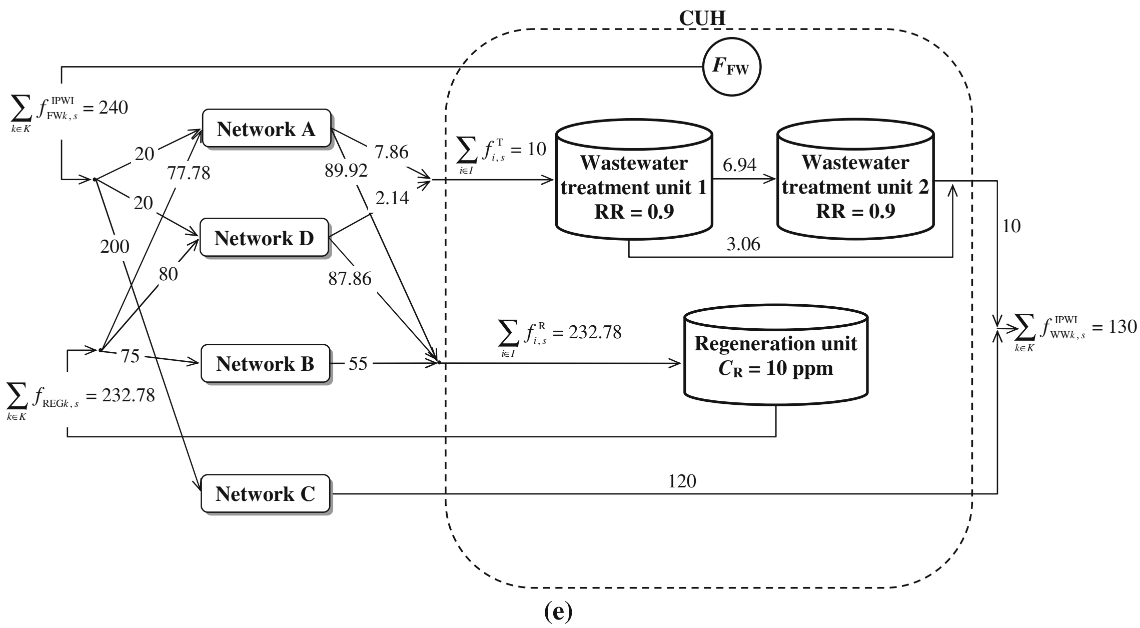

Fig. 2 continued

makes Schemes 1 and 5 the Nash equilibrium solutions for the external and internal payoffs, respectively. However, implementing Scheme 5 indicates that Network C will have to be eliminated from the IPWI scheme. Although Scheme 5 guaranteed the highest individual internal payoff (for Networks A, B and D), however, it does not possess the highest overall internal payoff ($857,720/*y*) as shown in Scheme 1.

In the following section, the IPWI schemes are analysed through cooperative game approach in which Pareto optimal solution is generated.

Cooperative game approach

Knowing the fact that there is always an imbalance segregation of benefits gained by each participating network, the policy maker (e.g. EIP authority, government, etc.) can play an important role to encourage the participation of the individual plant owners through policy setting (Salman and Cruz 1981; Ho et al. 1982; Cruz and Simaan 1999; Schwarz and Steininger 1997; UNEP 2009; Chertow 2007). In the cooperative game approach, it is assumed that a cooperative partnership between authority and the participating water networks is taking place in the IPWI scheme. In the proposed cooperative game, a market-based green incentive given by the EIP authority is introduced in the payoff evaluation. In this case, a uniform incentive is introduced to improve the environmental performance of the entire EIP (Bansal and Gangopadhyay 2003). The introduction of green incentive in the payoff evaluation will contribute to the overall increase of profits gained by each participating network.

Equation 15 shows the revised payoff adapted from Eq. 1, in which a market-based green incentive (G_s) is added on top of the internal payoff in the non-cooperative game. Fraction, x_s, in Eq. 15 represents the level of participation of an individual network in an IPWI scheme. As shown in Eq. 16, x_s is defined as the fraction of wastewater generation by network k' in the total wastewater flowrates when all networks participate in scheme s. Hence, the

Table 6 Evaluation of internal and external payoffs in non-cooperative game

Integration scheme s	Internal payoff $PY^{INT}_{k,s}$ ($/y)					External payoff PY^{EXT}_{s} (t/h)	
	k = A	k = B	k = C	k = D	Overall	$\sum_{k\in K} F^{save}_{k,s}$	$\sum_{k\in K} Q^{save}_{k,s}$
1. (Networks A, B, C, D)	201,723	210,883	235,560	209,554	857,720	292	292
2. (Networks A, B, C)	180,837	210,883	235,560	0	627,280	128	138
3. (Networks A, C, D)	184,521	0	235,560	192,352	612,433	152	172
4. (Networks B, C, D)	0	210,883	235,560	196,034	642,477	132	132
5. (Networks A, B, D)	236,129	210,883	0	243,960	690,972	12	92

Table 7 Green incentive for each integration scheme

Integration scheme s	Wastewater generation in participating networks k' (t/h)		Annual green incentive G_s (\$/y)	x_s
	Before IPWI $\sum_{k' \in K} f_{WWk'}$	After IPWI $\sum_{k' \in K} f^{IPWI}_{WWk',s}$		
1. (Networks A, B, C, D)	342	50	115,633	1.00
2. (Networks A, B, C)	260	40	116,161	0.76
3. (Networks A, C, D)	292	70	117,217	0.85
4. (Networks B, C, D)	252	30	117,215	0.74
5. (Networks A, B, D)	222	10	111,938	0.65

maximum incentive ($x_s = 1$) will be given if all four networks are participating in the IPWI. As shown in Eq. 17, the green incentive is directly proportional to the total amount of wastewater reduction and is shared equally among all participating networks $\left(N_s^{\text{Networks}}\right)$ in each scheme. The incentive rate (IR) is usually set by the policy maker and is given per unit of wastewater flowrate reduced.

$$PY^{INT}_{k,s} = ACS_{k,s} - R_{k,s} - P^{IND}_{k,s} + x_s G_s \quad \forall k \in K, \forall s \in S \tag{15}$$

$$x_s = \frac{\sum_{k'_s \in K} f_{WWk'}}{\sum_{k \in K} f_{WWk}} \quad \forall s \in S \tag{16}$$

$$G_s = \frac{IR\left(\sum_{k' \in K} f_{WWk'} - \sum_{k' \in K} f^{IPWI}_{WWk',s}\right) AWH}{N_s^{\text{Networks}}} \quad \forall s \in S \tag{17}$$

where k' denotes the participating networks in an integration scheme s.

Assuming the basis of green incentive rate (IR) of \$ 0.2/t wastewater reduction, the annual green incentive (G_s) calculated for each scheme is summarised in Table 7. As the first three terms in Eq. 15 denote the payoff in the non-cooperative game (see Eq. 1), the new internal payoff for cooperative game is obtained by summing the payoff in Table 6 with the annual green incentive in Table 7. For instance, the internal payoff for Network A in Scheme 2 is calculated as \$269,146/y (=116,161(0.76) + 180,837). Table 8 summarises the internal and external payoffs for the cooperative game approach. As shown, all networks gain additional internal payoff in all schemes due to the implementation of the green incentive, which internalizes the external costs. Besides, the external payoff component in each scheme remains identical to that of the non-cooperative game approach (see Tables 6, 8). As shown in Table 8, all four networks receive the highest individual annual internal ($PY^{INT}_{A,1} = \$317{,}356$, $PY^{INT}_{B,1} = \$326{,}516$, $PY^{INT}_{C,1} = \$351{,}193$, $PY^{INT}_{D,1} = \$325{,}187$) and external payoffs $\left(PY^{EXT}_1 = 292 + 292\right)$ by choosing Scheme 1. Note also in Scheme 1, Network C which was previously eliminated in the non-cooperative game is now being accepted in the cooperative game, which then generates an extra annual profit of \$351,193. It is important to note that, Scheme 1 of the cooperative game (Table 8) possesses higher individual internal payoff as compared to Scheme 5 in the non-cooperative game (Table 6). Scheme 1 is hence the Pareto optimal solution in a cooperative game. The inter-plant water network for this scheme is shown in Fig. 2a.

Sensitivity analysis

Sensitivity analysis is carried out to analyse the internal payoff for the Nash equilibrium solution in non-cooperative game (Scheme 5) and Pareto optimal solution in cooperative game (Scheme 1). In this example, the effect of the changes in wastewater treatment cost (ranges between \$2 and \$4 per kg load removed) is analysed. As shown in Figs. 3 and 4, the individual internal payoff for all participating networks increases proportionally with the wastewater treatment cost. This indicates that both Nash equilibrium and Pareto optimal solutions are robust to the fluctuation of wastewater treatment cost.

Table 8 Evaluation of internal and external payoffs in cooperative game

Integration scheme s	Internal payoff $PY^{INT}_{k,s}$ (\$/y)					External payoff PY^{EXT}_s (t/h)	
	k = A	k = B	k = C	k = D	Overall	$\sum_{k \in K} F^{save}_{k,s}$	$\sum_{k \in K} Q^{save}_{k,s}$
1. (Networks A, B, C, D)	317,356	326,516	351,193	325,187	1,320,252	292	292
2. (Networks A, B, C)	269,146	299,193	323,869	0	892,209	128	138
3. (Networks A, C, D)	284,601	0	335,640	292,432	912,673	152	172
4. (Networks B, C, D)	0	297,252	321,929	282,404	901,585	132	132
5. (Networks A, B, D)	308,790	283,545	0	316,621	908,956	12	92

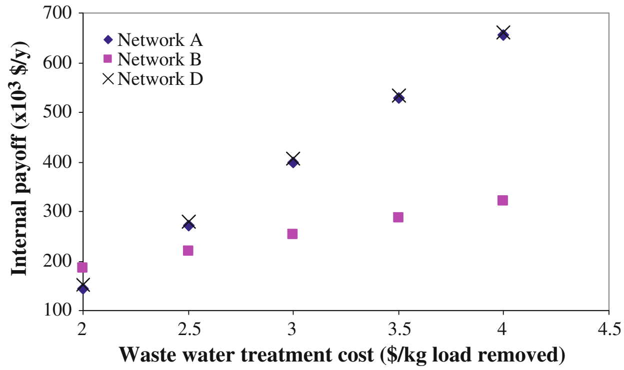

Fig. 3 Sensitivity analysis of wastewater treatment cost on internal payoff for Nash equilibrium solution in non-cooperative game (Scheme 5)

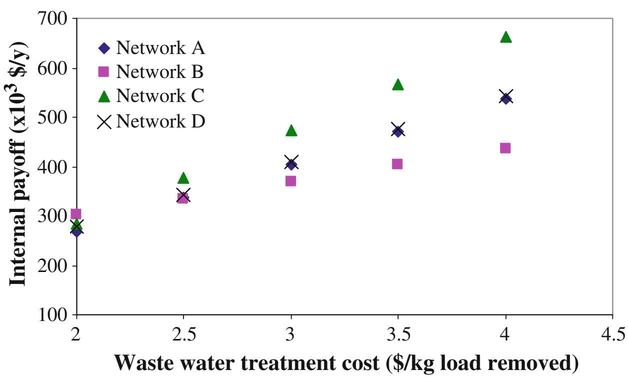

Fig. 4 Sensitivity analysis of wastewater treatment cost on internal payoff for Pareto optimal solution in cooperative game (Scheme 1)

Conclusion

A game theory-based approach is developed as a decision-making tool to analyse various indirect IPWI schemes. The intervention of the EIP authority in the form of providing green incentive induces the plant owners to cooperate among themselves in the IPWI scheme. Analysing the IPWI schemes through cooperative game will generate Pareto optimal solution, and exceed the individual payoffs that the players would receive under non-cooperative game. Although the proposed game theory model in this article is demonstrated for IPWI, it can readily be extended for other types of IPRCNs, including full-fledged EIP's involving exchange of multiple material and energy streams.

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