

Integrating input–output models with pinch technology for enterprise sustainability analysis

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Abstract This article proposes an integrated framework for enterprise sustainability assessment by integrating enterprise input–output modeling with water pinch analysis. Firstly, material metabolism of an enterprise is investigated to establish a baseline; then, potential for resource conservation and waste minimization is evaluated. The environmental performance and economic feasibility of modifications are then assessed based on identification of key processes. Thus, the framework provides a method to connect material metabolism analysis of enterprises with the implementation of specific actions for resource conservation and waste minimization. The case of the

water utilization system at Wangpo coal mine in China is used to illustrate the framework developed. Two process integration scenarios, involving direct reuse/recycle and regeneration, are presented. The corresponding revised input–output models for each scenario are illustrated.

Keywords Coal mine · Enterprise input–output model · Water pinch analysis · Sustainability

List of symbols

SR_i	Water source i
SK_j	Water sink j
F_{SR_i,SK_j}	Flowrate from SR_i to SK_j
F_{SR_i}	Flowrate of water source i
F_{SK_j}	Flowrate of water sink j
$F_{C,k}$	Cumulative flowrate at concentration level k
$\sum_i F_{SR_i}$	Total flowrate of water source i
$\sum_j F_{SK_j}$	Total flowrate of water sink j
$\sum_i F_{SR_i} - \sum_j F_{SK_j}$	Net flowrate at concentration level k
C_{SR_i}	Impurity concentration of water source i
C_{SK_j}	Impurity concentration limit of water sink j
C_k	Concentration level k of cascade table
Δm_k	Impurity load in each concentration interval k
$\text{Cum.}\Delta m_k$	Cumulative impurity load at concentration level k

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Introduction

Energy, environment, and sustainability concerns have posed challenges and opportunities for the industry (Agrawal and Sikdar 2012). Since industrial enterprises are

the basic units of production systems, enterprise-level environmental sustainability is essential to achieving sustainable development. As a result of increasing environmental problems and resource scarcity pressure on industry, it has become important to ensure sustainable business development, combining economic, social, and environmental aspects (Liang et al. 2012a). Enterprise-level environmental sustainability means producing cleaner products with less resource usage and waste generation (Piluso et al. 2008). Every enterprise interacts with other enterprises and the surrounding natural environment through material and energy flows (Liang et al. 2011a). A typical industrial plant draws resources from other enterprises and from the surrounding natural environment for production activities, while generating waste. This process is known as the *material metabolism* of enterprises (Liang et al. 2011b). Hence, a significant part of enterprise sustainability analysis focuses on investigating material metabolism. Currently, two categories of methods for enterprise sustainability analysis are often used: enterprise input–output (EIO) modeling and process systems engineering (PSE) approaches.

The EIO model can describe input and output flows of enterprises in either physical (e.g., mass flow) or monetary (i.e., economic value) terms (Albino et al. 2003). It has been widely used for analyzing material metabolism of production processes and supply chains. For instance, the EIO approach has been used to analyze New Zealand dairy products (Lenzen and Lundie 2012), tile manufacturing (Kutzt et al. 2010), bioenergy production (Yazan et al. 2011), and coal mining (Liang et al. 2011a). EIO-based approach for identification of process bottlenecks in industrial plants has recently been proposed (Tan et al. 2012b). Moreover, the combination of the EIO model with the geographic information system for supply chains analysis has also been developed (Albino et al. 2007). EIO models have also been used in conjunction with mathematical programming to optimize supply chains under water footprint constraints (Aviso et al. 2011). Furthermore, Tan et al. (2012a) presented a multi-region, fuzzy input–output optimization model for biomass production under resource and footprint constraints. Ewing et al. (2012) integrated ecological and water footprint accounting in a multi-regional input–output framework to identify key nodes within supply network that are responsible for changes in the environmental performance of the economy.

In our previous work, we combine the EIO model with scenario analysis to investigate material metabolism of enterprises (Liang et al. 2011a). The EIO model can elucidate direct and total material flows of production processes, providing holistic foundations for achieving sustainable production. Although the proposed model can

investigate the material metabolism of enterprises, it cannot identify potential scenarios for resource conservation and waste reduction. In order to solve this problem, PSE approaches are needed to optimize a site-wide industrial process. Among PSE approaches, *process integration* (PI) is regarded as the best-established approach for improving the sustainability (Klemeš 2013).

El-Halwagi (1997) defines PI as “a holistic approach to process design, retrofitting and operation which emphasizes the unity of the process.” This discipline develops efficient and systematic approaches that allow industries for analysis and design of processes and utility systems to increase both sustainability and profitability through reductions in energy, water and raw materials consumption, greenhouse gas emissions, and waste generation (Klemeš 2013). Among PI approaches, the insight-based *pinch analysis* techniques have been widely used in the past four decades in various industrial applications throughout the world, in parallel with corresponding developments in mathematical programming-based PI techniques (Klemeš and Kravanja 2013). Pinch analysis was originally developed for synthesis of heat exchanger network (Linnhoff and Hindmarsh 1983). Since then, many extensions were reported for various applications. *Mass integration* techniques were developed based on the analogies between heat and mass transfer (El-Halwagi and Manousiouthakis 1989). The concepts were then extended to related applications such as water network synthesis (Wang and Smith 1994) and property integration (Kazantzi and El-Halwagi 2005).

Beside the previously discussed applications, there are also other emerging trends of pinch analysis that are worth mentioning. Such extensions have emerged based on identification of analogous quality indices for different problems; for example, in the case of heat and mass integration, the quality indices that define the system driving force are temperature and concentration, respectively. In the case of carbon-constrained energy sector planning (Tan and Foo 2007), the quality of energy streams is defined by carbon intensity. Subsequent work proposed various measures of energy quality, such as land footprint (Foo et al. 2008), water footprint (Tan et al. 2009), and energy transformity (Bandyopadhyay et al. 2010). Many pinch extensions are based on the common use of time as the driving force; examples include off-grid hybrid energy systems (Wan Alwi et al. 2013), stand-alone hybrid system design (Bandyopadhyay 2011), power pinch analysis (Wan Alwi et al. 2012), production planning in supply chains (Singhvi and Shenoy 2002), biomass production planning (Ludwig et al. 2009), financial analysis (Zhelev 2005), and carbon capture and storage planning (Diamante et al. 2013). PI approaches have also been extended to inter-plant water network integration within industrial zones, which consider the

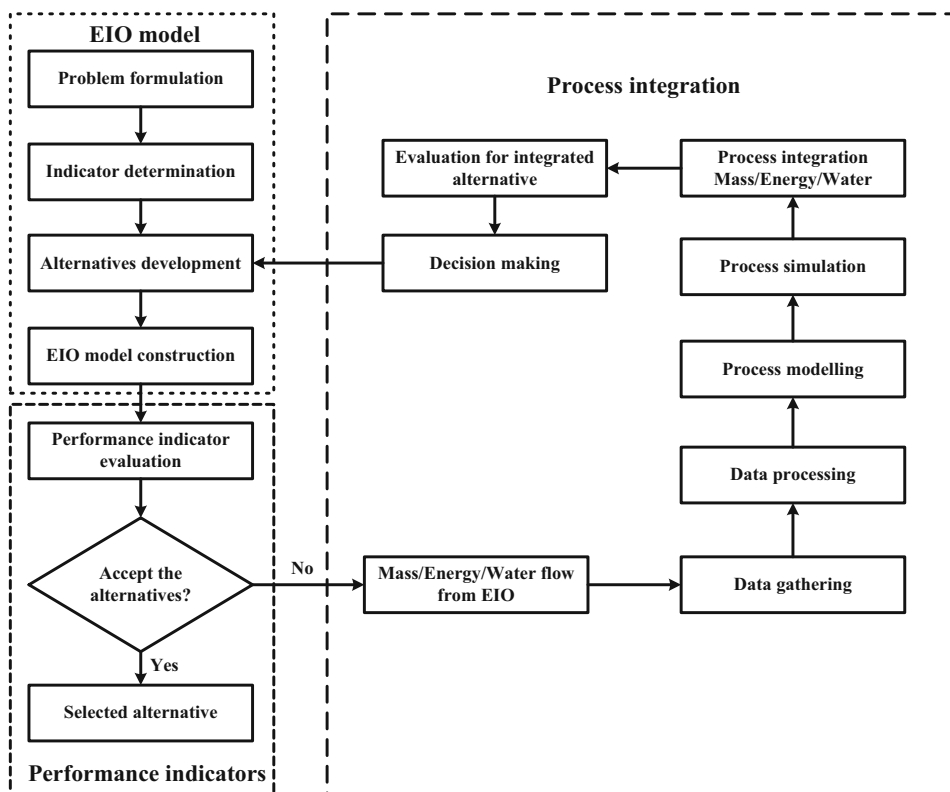
respective plant locations (Chew et al. 2010a, b) as well as the different quality restrictions of the plants involved (Bandyopadhyay et al. 2010). Recently, Jia et al. (2015) proposed an extended water pinch analysis based on the decomposition of total water footprint into external and internal footprint components. Furthermore, process innovation can be efficiently enabled through PI at multiple scales, starting from molecules and extending through process tasks, unit operations, plant wide, and finally at enterprise level (Varbanov and Seferlis 2014).

This work proposes an integrated framework for enterprise environmental sustainability analysis by combining EIO modeling with pinch analysis. The methodology is henceforth referred to as EIOPA and is first described in the succeeding sections. The EIOPA framework is then illustrated with the case of the Wangpo coal mine in China (Liang et al. 2011a). This industrial case is significant for a country whose dynamic growth is largely dependent of electricity production from coal (Zhang et al. 2014). As coal will remain a significant part of the energy mix due to its low projected cost (Shafiee and Topal 2010), it is essential to improve the sustainability of the coal sector through the use of carbon capture and storage (Wu et al. 2012) and by reducing the environmental impacts of upstream coal processing (Ou et al. 2011). Finally, conclusions and prospects for future work are given at the end of the article.

EIOPA methodology

The EIOPA framework for enterprise sustainability analysis is shown in Fig. 1. The resource allocation and waste generation of production processes and internal and external linkages of enterprises are described by the EIO model, while the potential for resource conservation in the enterprise is identified via pinch analysis. This framework is comprised three components: the EIO model, performance indicators, and PI. The EIO model can describe material metabolism of enterprises considering flows that occur both on-site and off-site, depending on the physical boundaries defined for the system (Lin and Polenske 1998). The indicators can then be used to evaluate the environmental and economic performance of an enterprise in order to establish a baseline against which future actions can be measured. PI can then identify potential for resource conservation. Any alternative processing scenario can then be developed to provide data inputs for constructing a new EIO model. Moreover, this framework can evaluate the feasibility of any proposed action by calculating their environmental benefits and monetary profit. Finally, it can anticipate possible metabolism scenarios arising from changes in the production system through the mathematical relationships of the EIO model. The prediction of possible metabolism scenarios, however, is not illustrated in the case study. The detailed descriptions of the framework components are provided in the following sections.

Fig. 1 The integrated framework for enterprise sustainability analysis



System definition and decomposition

The system is usually defined by enterprise boundaries. All major production activities within it are considered. Moreover, the system is decomposed according to its production processes. In this article, the case of Wangpo coal mine is revisited to illustrate this framework. Its system decomposition is the same as that in previous work (Liang et al. 2011a).

Enterprise input–output table construction

The EIO model in this framework extends the basic physical input–output process model introduced by Isard and Vietorisz (1955). This methodology has been extended for detailed process cost analysis within industrial plants (Lin and Polenske 1998). Following the convention used in EIO models, each major process is represented as a column vector of numbers indicating relative magnitudes of streams, with positive values indicating outputs and negative values indicating inputs. The conceptual structure of EIO model is shown in Table S1 of the Supporting Information (SI). The approach assumes fixed proportions which are based on relevant material and energy balances. Note that the approach works with any self-consistent set of units (e.g., mass flow or economic value). Moreover, two assumptions are made in the EIO model: each process produces only one main product and main products of each process cannot be consumed within the same process. For a detailed mathematical treatment of EIO model, the reader may refer to Lin and Polenske (1998).

The proposed EIO model can illustrate physical and monetary flows among production processes and that between the enterprise and other systems. The EIO model can describe material metabolism of enterprises, identify key processes from both direct and total perspectives for the implementation of actions, and foresee possible metabolism scenarios.

The EIO model can also be connected with the life-cycle analysis (Hendrickson et al. 2006), by converting pollutants of the EIO table to potential impacts through conversion factors. The input-output model is used for the life-cycle analysis to evaluate three alternative process residue utilization schemes (Kuan et al. 2007). However, using EIO model for the life-cycle analysis is not the emphasis of this work. Thus, this point is not described in detail.

Performance indicators

According to the “reduce, reuse and recycle” principle of the circular economy and the concept of environmental sustainability (Piluso et al. 2008), environmental assessment of the enterprises mainly focuses on the utilization levels of resources, the generation levels of wastes, and the recycling rates of wastes. In addition, the environmental

and monetary feasibility of new actions should be evaluated, because enterprises usually pay closer attention to their monetary profit, with less priority being given to their environmental performance. Thus, four categories of indicators are used in this framework, namely

- *Resource utilization* Direct and total input–output coefficients of the main products and purchased inputs in the EIO model indicate the consumption of resources drawn from external sources, such as the natural environment or suppliers.
- *Waste generation* Similarly, direct and total input–output coefficients in the EIO model can indicate the levels of emissions released to the environment, or by-products that may be used to generate additional revenues.
- *Waste recycling* The recycling rates of wastes can be calculated through their recycled amounts divided by their generated amounts. Alternatively, dimensionless indices such as those proposed for linear models of natural ecosystems (Finn 1976) and industrial ecosystems (Dai 2010) can be used.
- *Environmental benefits and monetary profit of new actions* The scenario after taking new actions (referred to as the new scenario here) is evaluated based on sustainability and economic considerations in comparison to the “business as usual” (BAU) baseline scenario. In principle, any conflicting goals can be addressed with the aid of multi-criterion decision analysis tools as proposed by Geldermann et al. (2006).

This framework evaluates the feasibility of actions by comparing the indicators with objectives derived from national and international standards. If the environmental benefits and monetary profit of new actions are both positive, these actions are feasible and they are implemented. If the environmental benefits or monetary profit of new actions are negative, these actions are infeasible. Potential problems can be identified according to comparison resulting scenarios. Then, other actions are proposed and material metabolism of the enterprise is optimized by pinch analysis, as shown in the following section.

Material metabolism optimization

PI tools are a widely accepted tool in optimizing mass and energy resource consumption, which allows waste reduction potential to be identified (Klemeš 2013). For some cases, PI tools identify new processing alternatives for the overall system. For a practical application, a step-wise framework for PI is shown in the dashed box within Fig. 1. The following procedure is needed for a typical PI study.

- *Data gathering* This involves the collection of the limiting process data from the baseline EIO model.

- *Targeting* Opportunities for resource conservation are identified using graphical, algebraic, or optimization tools. Various energy, water, and mass recovery networks may also be generated.
- *Process evaluation* Economic and environmental issues for various network alternatives are evaluated.
- *Decision-making* The results from the evaluation step are examined to identify improvement opportunities. The results are then used to generate a revised EIO model, for further analysis.

Pinch analysis is used in this work to identify potential for water minimization within the production facility. Steps in carrying out water pinch analysis study are given as follows, while a comprehensive treatment of the topic can be found in Foo (2012).

- Establish water balance diagram for production system of the enterprise;
- Identify the quantity (flowrate) and quality (impurity concentration) of all process water demands and sources;
- Identify the minimum amount of freshwater required and wastewater discharged by flowrate targeting tools [e.g., material recovery pinch diagram, water cascade analysis (WCA), etc.];
- Design a water recovery system that achieves the established targets.
- Obtain a new EIO table. Above steps will be repeated until actions are feasible.

Industrial case study

The case of Wangpo coal mine water system in China is revisited to illustrate this proposed framework. Relevant data are found in a previously published article (Liang et al. 2011a), but some additional data have been included in this work. Wangpo coal mine, located in Shanxi province, produces 1.5 Mt of coal/year. This coal mine is divided into seven main sections, namely, excavation, transportation, coal preparation, ventilation, mine water treatment, domestic water and heating, and sewage treatment. Detailed descriptions of these seven main sections and the schematic diagram of material flows at Wangpo coal mine are shown in a previous article (Liang et al. 2011a).

Enterprise input–output table construction

The BAU scenario is presented in Table S2 in the SI. Direct and total effects of production processes are calculated (Tables S3 and S4 in the SI). From the viewpoint of direct effects, excavation and domestic water and heating

consume the most resources, while three processes (excavation, coal preparation and domestic water and heating) discharge the most wastes. Thus, from the viewpoint of total effects, three processes, namely, coal preparation, domestic water, and heating and sewage treatment, are the major contributors.

Performance indicators

Selected indicators and objectives are listed in Table 1. Objectives are from national cleaner production standard (MEPPRC 2008), and all comparisons are relative to typical modern coal mines in other countries. According to results, utilization levels of resources at Wangpo are much better than those of modern coal mines. Concentrations of chemical oxygen demand (COD) and oil in mine water, however, are worse than those of benchmark levels at other modern coal mines. On the other hand, for coal preparation, the concentrations of COD and oil in wastewater, as well as coal gangue and dust concentration are slightly better than those found in modern coal mines. Finally, waste recycling rates at Wangpo are much worse than those found in modern coal mines. Methane gas drained out through the ventilation system, and mine water is totally discharged into natural environment. About 74.5 % of the coal gangue is abandoned in the barrow.

Based on this preliminary analysis, the following actions are proposed:

- Carry out water recovery between its process sinks and sources using direct reuse/recycle scheme or wastewater regeneration;
- Develop and construct a gangue sintered brick plant, which produces 60 million pieces of gangue sintered bricks every year, in order to improve the utilization rate of coal gangue;
- Replace the coal-fired boiler, which supplies electric and heat power, into a mine-gas-fired one and use the mine gas drained out through the ventilation system for the new boiler.

Note that pinch analysis is only used for water minimization study. The Wangpo Company authority decided to perform water recovery (rather than energy) as they are facing water scarcity issue in that region. Although energy saving issue may be incorporated within the proposed framework, it is not performed in this work.

Water minimization study

Direct reuse/recycle scenario and its EIO model

The limiting data for water minimization are given in Table S11 in the SI. The potential for direct water reuse/recycle is

Table 1 Results and comparisons for indicators of the Wangpo coal mine

Items	Units	Indicators ^a	Objectives (international advanced levels)
Utilization levels of resources			
Electricity required in raw coal production	kWh/t	9.5	15.0
Water required in raw coal production	m ³ /t	0.05	0.10
Wood required in raw coal production	m ³ /10 ⁴ t	3.7	5.0
Freshwater required in coal preparation	m ³ /t	0.02	0.1
Electricity required in coal preparation	kWh/t	2.2	5.0
Floating agent required in coal preparation	kg/t	0.02	1.00
Dense medium required in coal preparation	kg/t	0.4	1.5
Generation levels of wastes			
COD concentration of the mine water	g/t	448.6	100.0
Oil concentration of the mine water	g/t	22.3	6.0
COD concentration of coal preparation wastewater	g/t	24.0	25.0
Oil concentration of coal preparation waste water	g/t	1.3	1.5
Coal gangue production in coal mining	t/t	0.025	0.03
Dust concentration in coal preparation	mg/m ³	3500.0	4000.0
Recycling rates of wastes			
Utilization rate of mine gas	%	0.0	85.0
Comprehensive utilization rate of coal gangue	%	25.50	80.0
Utilization rate of the mine water	%	0.0	100.0

^a The calculation formulas of the indicators are listed in the “Cleaner production standard–Coal mining and processing industry” (MEPPRC 2008)

identified using an algebraic targeting technique, i.e., *water cascade analysis* (WCA; Manan et al. 2004). The results of WCA are shown in Table 2. As shown, concentration level (C_k) of all process sinks and sources are arranged in ascending order in column 1. Flowrates of the process sinks ($\sum_j F_{SKj}$) and sources ($\sum_i F_{SRi}$) are located at their concentration levels in columns 2 and 3 of the cascade table. At each level, the total flowrate of the process sinks is deduced from that of the process sources, with the net flowrate given in column 4 ($\sum_i F_{SRi} - \sum_j F_{SKj}$). The net flowrate is then cascaded from the highest to the lowest concentration levels in column 5 ($F_{C,k}$). The first and final entry of column 5 is identified as the minimum freshwater (F_{FW}) and wastewater (F_{WW}) flowrates of the water network. As shown in the cascade table, both the freshwater and wastewater flowrate are identified as 386.51 t/day. The pinch point is identified at 20 mg/L level.

Based on these process changes, direct and total effects of production processes are then calculated to derive the revised EIO model (Tables S5, S6, S7 in the SI). From the viewpoint of direct effects, excavation and domestic water and heating consume the most resources, while three processes (excavation, coal preparation, and domestic water and heating) discharge the most wastes. Moreover, from

the viewpoint of total effects, two processes named coal preparation and domestic water and heating are the major contributors.

The environmental benefit and monetary profit were performed as described in our previous work (Liang et al. 2011a). The unit cost for wastewater is 1.5 CNY/t. The unit supply price for wastewater is 2 CNY/t. Based on our previous work, the daily environmental benefit and monetary profit of proposed actions are also calculated, as given in Table 3. According to results, monetary profit and environmental benefits of proposed actions are both positive. Thus, these actions are feasible. In addition, coal preparation and domestic water unit are identified to be two key processes for environmental sustainable enterprise management of the Wangpo coal mine.

Wastewater regeneration scenario and its EIO model

When the potential for water flowrate reduction via reuse/recycle is exhausted, a common mean to further reduce the flowrates of freshwater and wastewater discharge is through water regeneration. An algebraic approach is used to determine the *ultimate flowrate targets* (i.e., minimum flowrates for freshwater, wastewater and regeneration) for

Table 2 WCA for direct reuse/recycle scenario

C_k (mg/L)	$\Sigma_j F_{SKj}$ (t/day)	$\Sigma_i F_{SRi}$ (t/day)	$\Sigma_i F_{SRi} - \Sigma_j F_{SKj}$ (t/day)	$F_{C,k}$ (t/day)	Δm_k (g/day)	Cum. Δm_k (g/day)
				$F_{FW} = 386.51$		
0				386.51	0.77	0.77
2	280.4		-280.4	106.11	0.85	1.62
10	408.5		-408.5	-302.39	-1.51	0.11
15		280.4	280.4	-21.99	-0.11	0.00
20		291.6	291.6	269.61	1.35	(Pinch)
25	55.7		-55.7	213.91	1.07	1.35
30		116.9	116.9	330.81	1.65	2.42
35		55.7	55.7	$F_{WW} = 386.51$	386,496.47	4.07
1,000,000						

a material regeneration network (Ng et al. 2007). The results are shown in Table 4. Detailed targeting steps are found in Tables S12, S13, S14, and S15 in the SI.

Cascade analysis determined that both the freshwater (F_{FW}) and wastewater (F_{WW}) flowrates are 196.7 t/day, while the total regeneration flowrate (F_{RW}) is identified as 329.8 t/day.

Similar to the direct reuse/recycle scenario, direct and total effects of production processes are then calculated to derive the new revised EIO model (Tables S8, S9, S10 in the SI). According to results, monetary profit and environmental benefits of proposed actions are both positive. Thus, these actions are feasible. The daily environmental benefits and monetary profit of proposed actions are also calculated, as shown in Table 5.

As compared to the base case scenario (with no water recovery), the water regeneration scenario features a freshwater saving of 73.6 %. Besides, the scenario also features 49.1 % of freshwater saving as compared to direct

reuse/recycle scenario. Summary of comparison for various water-using scenarios is shown in Table 6.

Network design

Nearest neighbor algorithm proposed by Prakash and Shenoy (2005) is used to design the water network for both direct reuse/recycle and regeneration scenarios. In order to design the minimum freshwater networks, the source streams to be chosen to satisfy a particular water demand must be the nearest available neighbors in terms of contaminant concentration. In other words, a source that is just cleaner and a source that is just dirtier than the demand are mixed to satisfy the demand. It is as possible as to mix the freshwater and regeneration water to meet the requirement of the sinks. The required amounts of these two sources (freshwater and regeneration water) are dictated by flow-rate balance and contaminant material balance equations, as given in Eqs. (1) and (2).

Table 3 The daily environmental benefit and monetary profit of proposed actions for direct reuse/recycle scenario

Items	Environmental benefits	Economic costs (CNY)	Economic benefits (CNY)	Net benefits (CNY)
Wastewater recycling	358.1 t/day	537.2	716.2	179.0
Coal gangue utilization	808.3 t/day	10,912.1	39,606.7	36,333.1
Mine gas utilization	13,657.8 m ³ /day	20,830.3	9400.0	-11,430.3
Total	-	32,279.6	49,722.9	25,081.8

Table 4 Cascade table for regeneration scenario

C_k (mg/L)	$\sum_j F_{SKj}$ (t/day)	$\sum_i F_{SRi}$ (t/day)	$\sum_i F_{SRi} - \sum_j F_{SKj}$ (t/day)	$F_{C,k}$ (t/day)	Δm_k (g/day)	Cum. Δm_k (g/day)
				$F_{FW} = 196.70$		
0				196.70	0.39	
2	280.4		-280.4			0.39
				-83.70	-0.39	
6.7		$F_{RW} = 329.78$	329.78			0.00
				246.08	0.81	
10	408.5		-408.5			0.81
				-162.42	-0.81	
15		162.42	162.42			0.00
				0.00	0.00	(Pinch)
20		135.5	135.5			0.00
				135.50	0.68	
25	55.7		-55.7			0.68
				79.80	0.40	
30		116.9	116.9			1.08
				196.70	0.98	
35			0			2.06
				$F_{WW} = 196.70$	196,696.91	
1,000,000						196,696.91

Table 5 The daily environmental benefits and monetary profit of proposed actions for water regeneration scenario

Items	Environmental benefits	Economic costs (CNY)	Economic benefits (CNY)	Net benefits (CNY)
Wastewater recycling	547.9 t	821.9	1095.8	273.9
Coal gangue utilization	808.3 t	10,912.1	39,606.7	36,333.1
Mine gas utilization	13,657.8 m ³	20,830.3	9400.0	-11,430.3
Total	-	21,652.2	50,102.5	25,176.7

Table 6 Summary of comparison for various water-use scenarios

Flowrate targets	Base case	Direct reuse/recycle	Regeneration
Freshwater, F_{FW} (t/day)	744.6	386.51	196.7
Wastewater, F_{WW} (t/day)	744.6	386.51	196.7
Regeneration water, F_{RW} (t/day)	-	-	329.8

$$F_{SRi,SKj} \times C_{SRi,SKj} + F_{SRi+1,SKj} \times C_{SRi+1,SKj} = F_{SKj} \times C_{SKj}, \tag{1}$$

$$F_{SRi,SKj} + F_{SRi+1,SKj} = F_{SKj}, \tag{2}$$

where $F_{SRi,SKj}$ is the allocation flowrate sent from SR_i to SK_j , two source candidates SR_i (with flowrate F_{SRi} and quality C_{SRi}) and SR_{i+1} (with flowrate F_{SRi} and quality C_{SRi}) to fulfill the flowrate and load requirements of sink SK_j .

Since all sinks are fulfilled, the leftover flowrate in sources are discarded as wastewater. Figures 2 and 3 present the water network for direct reuse/recycle and regeneration scenarios, respectively.

Conclusions

Sustainability has become a key factor in modern enterprise-level decision-making. This work develops an integrated EIOPA framework for enterprise environmental sustainability analysis by integrating EIO model with PI and pinch analysis. The proposed framework can investigate material metabolism at the enterprise level, identify potential of resource conservation and waste recycling, evaluate environmental performance of alternative actions (such as waste recycling), and identify key processes from both direct (site level) and total (production chain)

Fig. 2 Water network for direct reuse/recycle scenario (units t/day)

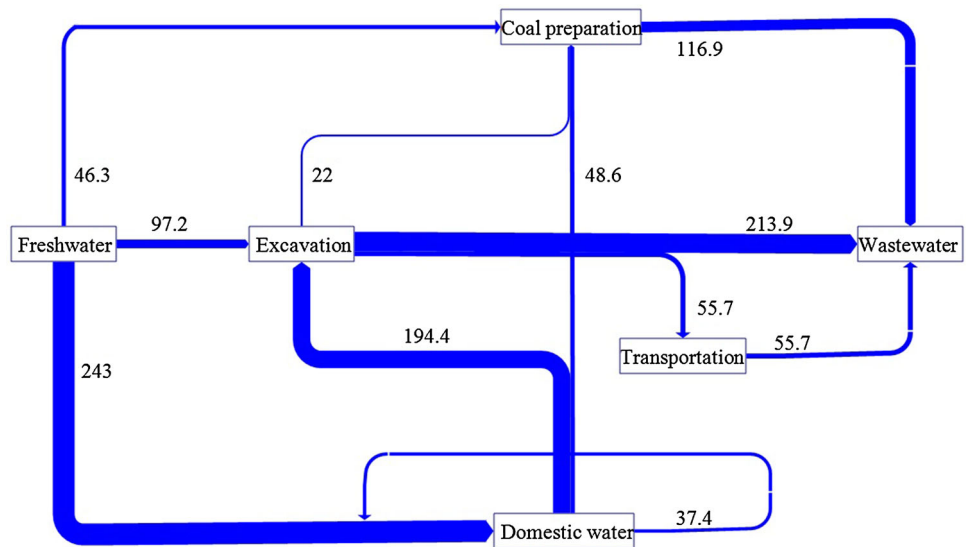
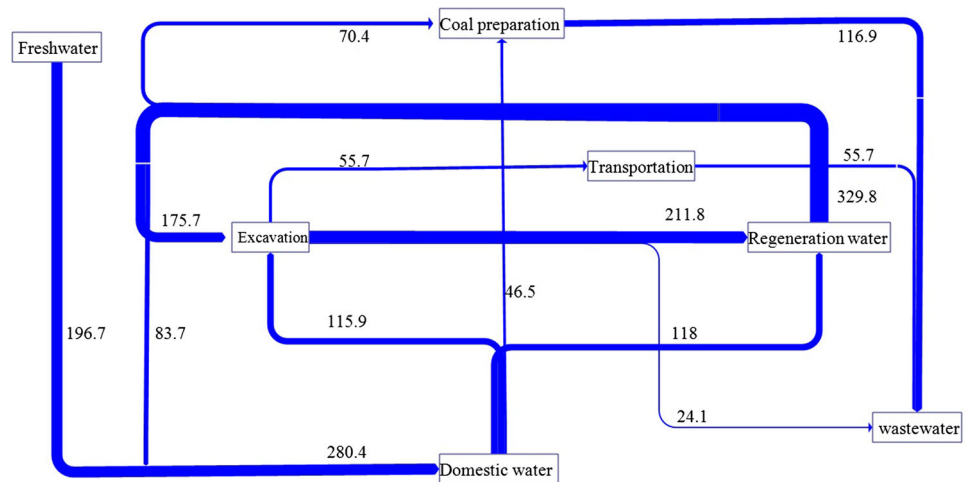


Fig. 3 Water network for regeneration scenario (units t/day)



perspectives. It is thus possible to systematically evaluate the consequences of the implementation of actions and foresee possible metabolism scenarios. The case of Wangpo coal mine water system is revisited to illustrate the proposed framework. This framework is suitable for company managers and public administrators to evaluate enterprise performance in the context of multi-dimensional sustainability planning.

Since the energy is consumed in the form of electricity in this case study and Wangpo has the pressure of carbon reduction, power pinch analysis can be used to design the grid power system in future work. On the other hand, energy–water nexus works in both process and site levels, which means in the same way energy use and water use amplify each other, also energy and water saving can amplify each other (Varbanov 2014). The EIOPA framework can also be

readily extended to industrial problems involving general PI, where utilities such as energy and water are considered simultaneously. Furthermore, the evaluation of proposed actions should be combined with the analysis of production chains using a life-cycle perspective, because positive actions in a particular enterprise may have negative external effects (Liang et al. 2012b). This extension might require the combination of EIO model with economy-wide hybrid input–output models (Liang and Zhang 2013) or life-cycle assessment models. In this way, the feasibility of the actions can be validated from both on-site (i.e., enterprise level) and life-cycle (i.e., production chain) perspective, which can provide more comprehensive information for sustainability planning. In addition, current methodology can also be readily extended for enhancing the sustainability of eco-industrial parks.

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