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Inoperability Input-Output Models for Water System in Industrial Parks

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Increasingly frequent disturbances such as droughts, earthquakes and terrorist attacks have severely affected the interdependent infrastructure of industrial parks. It is necessary to explore the relationship between the interdependence degree and stability of the infrastructure and ensure that the infrastructure systems can withstand the impact of emergencies from natural disasters, industrial accidents, or malicious attacks. The water system of an industrial park is investigated in this work, which proposes a method combining Process Integration with the inoperability input-output model (IIM) for risk analysis. First, Process Integration is used to generate optimal water network alternatives under different optimisation conditions. The IIM was next established to investigate the inoperability, elasticity, and flexibility of each alternative after a disturbance occurs. Finally, practical risk mitigation measures are discussed based on the analysis. Results showed that when PI is used to help the park save water, it also leads to the high interdependency, which makes the park difficult to withstand the shock of external disturbances and causes cascading damage.

1. Introduction

The infrastructure of an eco-industrial park (EIP) is necessary to ensure steady operation of the plants in the site. However, the frequent occurrence of emergencies due to natural disasters, industrial accidents, or deliberate attacks has caused serious impacts on interdependent infrastructure. A systematic analysis of the interdependence between critical infrastructures is necessary (Utne et al., 2011). Extended from the Leontief input-output model (Haimes and Jiang, 2001), the inoperability input-output model (IIM) can be used to account for the propagation effect of the interdependence in the infrastructure system. Tan et al. (2014) used a fuzzy IIM to analyse the risk of a biodiesel park in the Philippines. Ocampo et al. (2016) took a furniture factory as an example to investigate the disturbance caused by rising manufacturing costs. Kuznetsova et al. (2017) combined the IIM with the expert method to analyse the Kalundborg EIP. As an effective means of water conservation and wastewater minimisation, Process Integration (PI) is widely used in the design and optimisation of water networks (Foo, 2009). The stability of water networks has also been studied. For example, Aviso (2014) proposed robust water networks for eco-industrial symbiosis to maintain efficient operations in different situations. Soldi and Candelieri (2015) used complex network theory to evaluate the resilience and vulnerability of water distribution networks. In order to explore the relationship between the interdependence degree and stability of the EIP infrastructure, this paper proposes a method combining PI with the IIM for risk management. A case study is conducted in an EIP to investigate the influence of infrastructure interdependence on stability. It will ensure that the EIP can avoid or reduce economic losses under the impact of external disturbance to achieve the goal of saving water in a steady state.

2. Methodology

An integrated PI and IIM framework for sustainable water management in EIPs is developed. The PI-based model deals with the issues about how the water is reused between different water-using plants. This optimisation model is solved first to generates multiple optimal water network alternatives under different

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conditions. The interdependencies of the base case and all the alternatives are then analysed. The interdependence matrix of each alternative is constructed. The IIM is established to calculate the inoperability, elasticity and flexibility of each alternative after disturbance occurs.

2.1 Inoperability input-output model

The supply-side inoperability input-output model (SIIM) is an effective tool for quantifying the impacts on sectors affected directly by man-made or natural disasters, as well as the impacts on the other sectors of the system due to the cascading effect of interdependence. It provides a model of how interdependence in different sectors leads to destruction propagation. Inoperability is defined as the degree to which a system fails to perform its intended function due to internal failure or external disturbance. It ranges from 0 (normal) to 1 (completely failed). The SIIM is as follows (Leung and Haimes, 2007):

$$p = (I - A^{(S)*})^{-1} z^* \tag{1}$$

$$A^{(S)*} = diag(\hat{x})^{-1} A^{(S)} diag(\hat{x}) \tag{2}$$

Elasticity evaluates the ability of a network system to recover its initial or ideal state after disruption occurs. Flexibility evaluates the system’s ability to respond correctly and quickly to changes in internal and external environments. In this study, the elasticity coefficient is used as the criterion to evaluate the strength of elasticity, while the flexibility index is used to evaluate the network flexibility.
The elasticity coefficient is calculated using Eq(3) (Schoenwald et al., 2009):

$$k_i = \frac{ln[q_i(0)/q_i(T_i)}{T_i}\left(\frac{1}{1-a_{ii}^*}\right) \tag{3}$$

The flexibility index is calculated as follows:

$$\mathrm{Flex} = 0.5\mathrm{UN} + 0.5\mathrm{CN} \tag{4}$$

$$UN = \sum_{i=1,j=1}^{n} D_{ij} \qquad D_{ij}\text{=0,}(i,j\text{ is not connected); }D_{ij}\text{=1,}(i,j\text{ is connected)} \tag{5}$$

The unit connection number is the total number of connections between units in the network. The smaller the number of unit connections, the simpler is the network structure, and the higher the flexibility of the system. The additional control number is the total number of units that receive water from other units in the network. When the number of additional controls is small, water-using units in the network is less likely to be affected by changes in the operation of other units, and the system flexibility is high.

2.2 PI for water systems

In this paper, it is considered that wastewater from water-using units and regeneration units may be reused, recirculated and recycled for water saving. In addition, different optimal water network alternatives are generated for different optimisation conditions of the target EIP. The optimisation model is presented below (Tsai, 2017).
Water flowrate balances for water-using units:

$$F_i = \sum_{j \in J} f_{ij} + \sum_{d \in D} f_{id} + \sum_{k \in K} f_{ik} \tag{6}$$

$$F_j = \sum_{i \in I} f_{ij} + \sum_{r \in R} f_{rj} + \sum_{k \in K} f_{kj} \tag{7}$$

Water flowrate balances for regeneration units:

$$\sum_{i \in I} f_{ik} = f_k \tag{8}$$

$$f_k = \sum_{j \in J} f_{kj} + \sum_{d \in D} f_{kd} \tag{9}$$

Logical constraints:

$$F_{ij}^L \le f_{ij} \le F_i z_{ij} \tag{10}$$

$$F_{ik}^L \le f_{ik} \le F_i z_{ik} \tag{11}$$

$$F_{kj}^L \le f_{ik} \le F_i z_{kj} \tag{12}$$

The objective function is to maximize the cost saving from the retrofit:

$$\max \chi = CWS^{ori} - CWS - PC - RC \tag{13}$$

$$CWS = AOH \sum_{r,j} C_r f_{rj} \tag{14}$$

$$PC = \sum_{i \in I, j \in J} C_{ij}^{add} + \sum_{i \in I, j \in J} C_{ij}^{re} \tag{15}$$

$$RC = C_{ua} S + C_{const} \tag{16}$$

Eqs(6)-(9) are the water balance constraints for the inlet and outlet of water-using units and regeneration units. In Eqs(10)-(12), binary variables z_{ij}, z_{ik}, and z_{kj} are introduced to indicate whether the connection exists or not. As given in Eq(13), the cost saving is defined as the difference in water supply cost between the existing and retrofitted water networks minus the cost of piping retrofits and the cost of regeneration. The cost of water supply is given by Eq(14). As shown in Eq(15), each connection between units in a water network requires a pipe. The cost of the pipeline includes the installation and removal costs of the pipeline. Eq(16) gives the capital cost of the regeneration unit.

3. Case study

There are six plants in a hypothetical EIP, namely, plant A, B, C, D, E and F. The details of the EIP are taken from Tsai (2017). The limiting data for the case study are shown in Table 1. Plants E and F have no outlet flowrate because water entering these plants are embedded in the products. The annual operating time for the EIP is 8,000 h, the cost of freshwater supply is $ 0.15 /t. The unit area fixed cost for regeneration equipment is $ 2,310 and the variable cost of construction for the regeneration unit is $ 260,292 (Tan et al., 2007). The PI approach is adopted to optimise the water network in the EIP. Assume that the freshwater supply from the 1,989.06t/h to the park decreases by 20 % due to drought. It is necessary to calculate and compare the stability of the base case and six different alternatives. The stability of the park is evaluated by (1) inoperability, (2) elasticity, and (3) flexibility. It is assumed that there is no standby water supply in the park.

Table 1: Operating conditions of each unit

Plants	Inlet		Outlet	
	Flowrate (t/h)	Concentration (ppm)	Flowrate (t/h)	Concentration (ppm)
A	155.40	20	155.40	100
B	831.12	80	1,305.78	230
C	201.84	100	201.84	170
D	1,149.84	200	469.8	250
E	34.68	20	-	-
F	68.7	200	-	-

Table 2: Different conditions and optimisation results

	Conditions	Freshwater (t/h)	Wastewater (t/h)	Regenerated water (t/h)	Cost saving ($)
Base case		1,989.06	1,680.3		
OA1	Direct water reuse	847.12	529.36		1,360,619
RA1	One regeneration unit	308.76		1,491.135	1,333,602
OA2	The water flowrate between the	850.14	539.36		1,360,966
RA2	plants is not less than 20 t/h	306.16		1,491.295	1,333,209
OA3	Expands the distance to 5 times,	891.996	583.23		1,277,461
RA3	and the flowrate is not less than 20 t/h	306.426		1,048.62	1,245,699

3.1 Inoperability under assumed perturbation value

Figure 1 shows the water network of the base case.

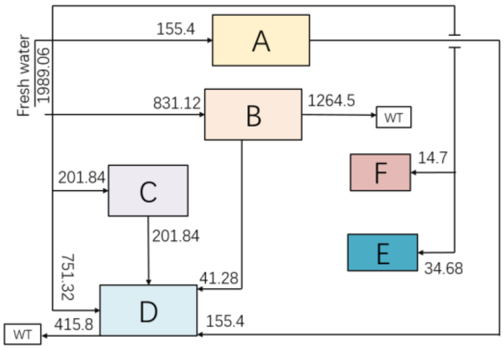
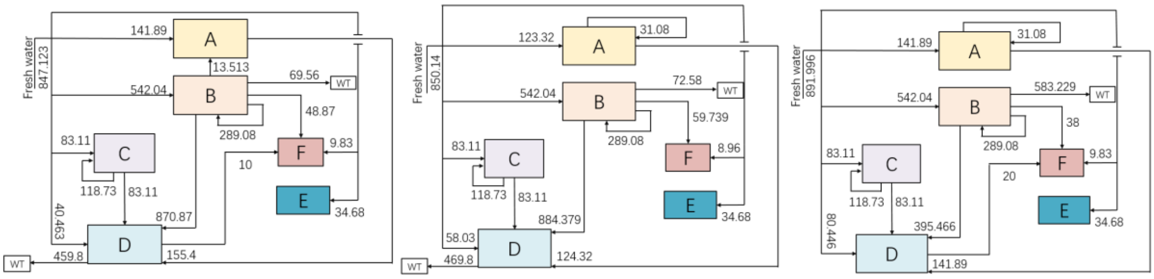


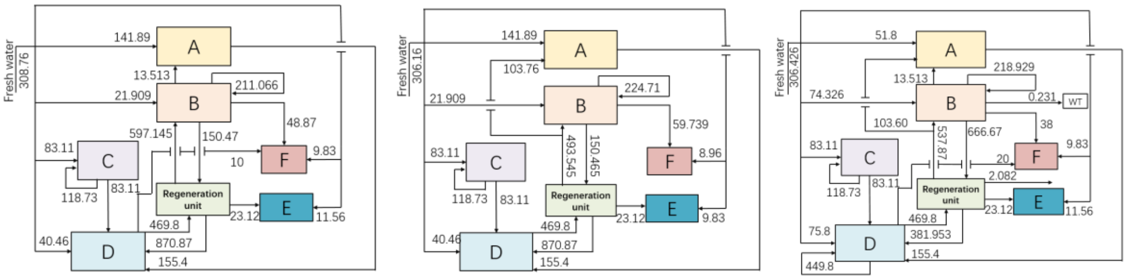
Figure 1: Water system of the base case with flowrates in t/h

Under different conditions (see Table 2), the operating conditions of each water-using plant (see Table 1) and the distances between plants, the mathematical programming model is used to optimise the water networks. Three optimisation alternatives (OA1-3) are obtained as shown in Figure 2, and three regeneration alternatives (RA1-3) in Figure 3. The optimisation results (see Table 2) and the inoperability values of the seven different plans (in Figure 4) are then calculated.



(a) OA1 (b) OA2 (c) OA3

Figure 2: Water network system of (a) OA1 (b) OA2 (c) OA3 with flowrates in t/h



(a) RA1 (b) RA2 (c) RA3

Figure 3: Water network system of (a) RA1 (b) RA2 (c) RA3 with flowrates in t/h

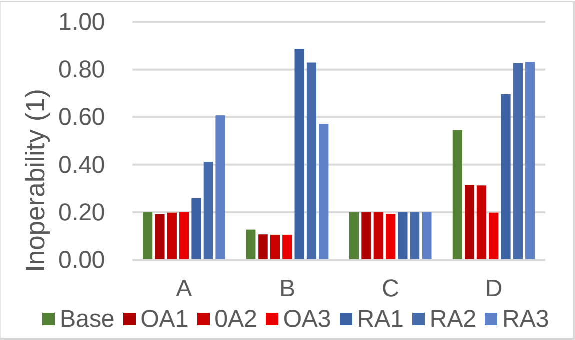


Figure 4: Inoperability values

In this specific case study, the inoperability value of each OA case is less than that of the base case. This means that the OAs are more capable of overcoming the impacts of the disturbance of water supply. In all the scenario, the water supplier for plant B is the same. The water supplier of plant D is changed from the freshwater to plant A. As the demand for freshwater in plant B decreases, the disturbance in the two plants decreases. In general, the increase in the number of water supply channels for each alternative weakens the relationship between the plants and the upstream water supply station. When the water supply from the fresh water station decreases, the impact on the plants in the park decreases.

In this specific case study, the inoperability value of each RA case is higher than that of the base case. This means that the RAs are less capable of withstanding impacts and a higher degree of disturbance. All the wastewater from plant B and plant D is sent to the regeneration unit and is re-supplied to other plants. The water supply from the freshwater plant is fully utilized in the park. Due to the addition of the regeneration unit, the flow mode of freshwater has changed from "freshwater station—plant—wastewater discharge" to "freshwater station—plant—regeneration unit—plant". The existence of a regeneration unit deepens the interdependence between plants. When the supply of freshwater station decreases, the disturbance propagates gradually in the park due to the interdependence, multiplying the disturbance.

3.2 Evaluation of elasticity coefficient and flexibility index

Elasticity coefficients and flexibility indices for each alternative are shown in Figures 5(a) and 5(b). The elasticity of each OA case is higher than that of the base case. The OAs have better ability to recover to the initial state. In the OA, plants B and D suffer less from disturbance than in the base case due to the increase in the number of water supply channels after the initial disturbance, and the multi-source water supply channels give plants B and D better recovery ability. The smaller disturbance value and the higher recovery capacity result in higher elasticity coefficients for plants B and D to recover to the original state faster.

The elasticity of each RA case is smaller than that of the base case**.** The RAs have less ability to recover to the initial state. In the RA, plants A, B and D suffer from a serious disturbance under the influence of interdependence. When the freshwater station can supply water normally, the new water supply channel requires the plant to wait for the related water supply station to restore before getting the normal water supply.

The flexibility of the base case is greater than that of the alternatives**.** This indicates that complex systems are less able to respond quickly to external changes and adapt to changes than simple systems. As a result of the increase in the number of connected units in a complex system, the change of a unit will affect the whole complex network due to the interdependence.

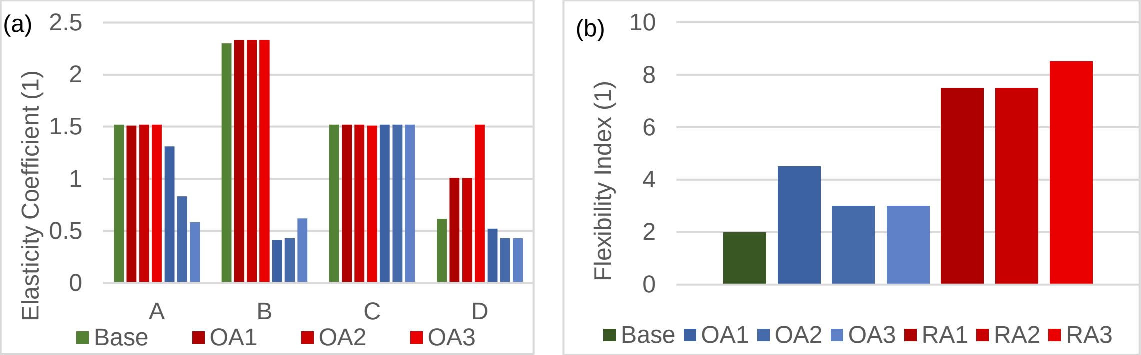


Figure 5: (a) Elasticity coefficient; (b) Flexibility index

4. Conclusions

This work investigated the influence of the stability of water networks under water supply failure in industrial parks using a hybrid PI and IIM approach. It was found that there is a trade-off between the capability of a water network to withstand shocks and its capacity to use water resources efficiently. The tight integration needed to achieve low levels of water consumption makes water networks more vulnerable to cascading failure. The limitation of this study is the flow data of the water network must be accurate, and when the output does not belong to the water network, the inoperability of the water unit cannot be calculated. Future work will focus on more accurate data, scenarios of different triggering conditions and risk mitigation solutions that can guarantee the safe and stable operation of the park and achieve the purpose of optimization (e.g., multiple water sources).

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Nomenclature

$i \in I$	Water-using units
$j \in J$	Water-using units
$k \in K$	Regeneration units
$r \in R$	Freshwater
$d \in D$	Wastewater
a_{ii}^{*}	A diagonal member of the incidence matrix A^{*}
$A^{(S)*}$	The supply incidence matrix for infrastructure
AOH	Annual operating time
CN	Additional control
C_{ua}	Unit area fixed cost of regeneration equipment

C_{const}	Variable cost of construction for regeneration unit
C_r	Cost of freshwater
CWS	Cost of water supply
C_{ij}^{add}	Cost of adding pipelines between i and j
C_{ij}^{re}	Cost of removing pipelines between i and j
$diag(\hat{x})$	A diagonal matrix of the total output of all units
D_{ij}	The number of connection decisions
F_i	Total outlet flowrate of water source i
F_j	Total inlet flowrate of water unit j
F_{ij}^L	The minimum flowrate of the pipeline between i and j
UN	Unit connection number
p	Abnormal horizontal vector of an interdependent system
PC	Cost of pipeline
$q_i(0)$	The initial abnormal level
$q_i(T_i)$	The abnormal level at time T_i
RC	Cost of regeneration unit
S	Area of regeneration unit
z	The initial perturbation vector

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