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Water Network Optimisation with Consideration of Network Complexity

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This paper presents a superstructural model for the synthesis of water network, with the objective to reduce its complexity. A less complex network will ease its operation. Different constraints are added to the model, i.e. reduced piping length and number of piping connections. Literature case study comprises of ten water-using processes is used to demonstrate the approach.

1. Introduction

Mass integration was extended by El-Halwagi and Manousiouthakis (1989) from heat integration (Linnhoff et al., 1982), following the analogy of heat and mass transfer. Water minimisation was then developed by Wang and Smith (1994) as a special case of mass integration. The main driving force for the developments of water minimisation is the awareness on environmental sustainability, which calls for the efficient use of water resources among industrial processes (Sueviriyapan et al., 2014). Insight-based pinch analysis and mathematical optimisation are the two major approaches developed rapidly in the past decades (Foo, 2012). Superstructural approach is one of the commonly-used mathematical optimisation technique for water minimisation. In recent years, some works on mathematical optimisation were reported for pre-treatment system (Ahmetović and Grossmann, 2011), as well as flexible network synthesis (Poplewski, 2014). In this paper, a superstructural model that incorporates different process constraints is proposed to synthesise a water network for the ease of process operation.

When water minimisation is implemented for process plants with many water-using processes, it may lead to complex piping system. This may lead to controllability issue, due to the decrease in its degree of freedom. A less complex network is always desired as it will reduce operational and controllability issues of the process plant. Different model-size reduction techniques had been developed for different areas of process integration work. Lam et al. (2011) presented few model-size reduction techniques for large-scale biomass production and supply network. Amidpour and Polley (1997) presented decomposition approaches for heat exchanger network synthesis. Ng et al. (2012) on the other hand, decomposed an integrated heat exchanger network by dividing the integrated structure into two or more clusters. In this work, a superstructural model is developed to enable the synthesis of a less complex water network, which considers piping length and number of piping connections.

2. Model formulation

In this section, the basic superstructural model for a water network is outlined.

The objective function for the decomposition model is to minimise the total annual cost:

$$\text{Minimise } TAC \tag{1}$$

For a water reuse/recycle network, this model has the following constraints:

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i) Flowrate balance for process sources.
Each process water source *SRi* may be allocated to the water sinks *SKj*, in which its allocated flowrate is denoted as $F_{SRi,SKj}$. Unutilized source would be directed to waste disposal (*WW*), with flowrate term $F_{SRi,WW}$. Eq(2) describes the overall flowrate balance for process source *SRi*, where F_{SRi} denotes the total flowrate of source *SRi*.

$$\sum_{SKj} F_{SRi,SKj} + F_{SRi,WW} = F_{SRi} \qquad \forall\ SRi \in SRI \tag{2}$$

ii) Flowrate balance for process sinks.
Each process water sinks have flowrate requirement, F_{SKj}, which can be fulfilled by process sources ($F_{SRi,SKj}$) or fresh resource (*FW*), with flowrate term $F_{FW,SKj}$. Eq(3) describes the overall flowrate balance of process sink *SKj*.

$$\sum_{SRi} F_{SRi,SKj} + F_{FW,SKj} = F_{SKj} \qquad \forall\ SKj \in SKJ \tag{3}$$

iii) Contaminant load requirement.
The amount of contaminant load from sources and fresh resource feed should not exceed the maximum limit of each process sinks, which is given by Eq(4). Source quality is denoted as q_{SRi} and fresh resource quality is denoted as q_{FW}. The maximum contaminant concentration of sink *SKj* is denoted as q_{SKj}.

$$\sum_{SRi} F_{SRi,SKj} \cdot q_{SRi} + F_{FW,SKj} \cdot q_{FW} \geq F_{SKj} \cdot q_{SKj} \qquad \forall\ SKj \in SKJ \tag{4}$$

In order to reduce the model's complexity, two aspects are considered, i.e. number of piping connections and piping length.

To consider number of piping connections, a binary variable $B_{SRi,SKj}$ is introduced in the model. The binary variable is activated using Eq(5):

$$\frac{F_{SRi,SKj}}{M} \leq B_{SRi,SKj} \tag{5}$$

where *M* is an arbitrary large value.

The total number of pipelines, *NP*, in the network is given by:

$$NP = \sum B_{SRi,SKj} \tag{6}$$

An upper bound for the total number of pipeline, NP^{UB}, is introduced such that the total pipelines does not exceed the maximum limit, as the number of pipelines are used to measure the complexity of the network:

$$NP \leq NP^{UB} \tag{7}$$

To limit the total length of piping connection in the network, *PL*. Eq(8) is used:

$$PL = \sum D_{SRi,SKj} \cdot B_{SRi,SKj} \tag{8}$$

An upper bound for the total piping length, PL^{UB}, is defined in which the synthesised network should not exceed the given upper bound, which will confine the area of the network.

$$PL \leq PL^{UB} \tag{9}$$

It is important to consider the cost element of a water network. The estimation of piping cost (*CC*) and operating cost (*OC*) are used to calculate the total annualised cost (*TAC*) of the network.

The piping cost correlation includes variation (*a*) and fixed (*c*), given as in Eq(10). The coefficient *a* accounts for the linear impact of flowrate on the capital cost of piping; whilst, the fixed term *c* is a constant value that describes the basic capital cost contribution. The capital cost is directly affected by the distance or length of the connections between the process sinks and sources, $D_{SRi,SKj}$.

$$CC = \sum_{SRi} \left(aF_{SRi,SKj} + c \right) \times D_{SRi,SKj} \tag{10}$$

The distance between two unit operations is calculated as the modular sum of difference in each axis due to the piping characteristic defined:

$$D_{SRi,SKj} = \left| X_{SRi} - X_{SKj} \right| + \left| Y_{SRi} - Y_{SKj} \right| \tag{11}$$

where X and Y are coordinates of the sinks and sources. The distances are assumed to be straight lines in the x-axis and the y- axis.

Operating cost takes into consideration of fresh water (with unit cost CT_{FW}) and waste discharge (with unit cost CT_{WW}), as shown in Eq(12):

$$OC = \sum\nolimits_{SKj} F_{FW,SKj} CT_{FW} + \sum\nolimits_{SRi} F_{SRi,WW} CT_{WW} \tag{12}$$

The total annual cost, *TAC*, is then calculated by Eq (13):

$$TAC = OC \cdot AOT + CC \cdot AF \tag{13}$$

where annual operating time (*AOT*) is taken as 8000 h and the annualising factor (*AF*) is then calculatedusing:

$$AF = \frac{IR(1+IR)^y}{(1+IR)^y - 1} \tag{14}$$

3. Example

A literature example is adapted from Savelski and Bagajewicz (2001), compromises of ten water-using processes is used to demonstrate the proposed approach. The streams data of the case study is presented in Table 1. A direct reuse/recycle network with minimum freshwater consumption and total cost was synthesised using the superstructural model. The mixed-Integer Linear programming (MILP) models are formulated and solved using LINGO v14.0.

In this work, three cases are solved with constraints in Eq(2) toEq(4) and Eq(10) to Eq(14) and objective function in Eq(1): (i) case 1: a base case model that minimises fresh water flowrate, (ii) case 2: minimum flowrate constraint is embedded for the piping connections, the total number of pipelines and individual pipe lengths are then used in case 3 as the upper boundary; and (iii) case 3: with maximum total number of pipeline of 23 pipes and piping length of 700 m, which are the maximum predefined from Model 2. The capital cost is calculated using Eq(10), where constants *a* takes the value of 2 and *c* takes the value of 250. On the other hand, annual fractional interest rate, *IR*, of 5 % and 5 y is considered for Eq(14). The network designs of all cases are found in Figures 1-3, while the stream flowrates are tabulated in Table 2-4, and their comparison in Table 5.

Table 1: Stream data for case study

Process Number	**ΔM_p (kg/h)**	**C_{in}^{max} (ppm)**	**C_{out}^{max} (ppm)**	**F_p (t/h)**	**x-coordinates (m)**	**y-coordinates (m)**
1	2.00	25	80	36.4	36.36	661.82
2	2.88	25	90	44.3	250.00	604.55
3	4.00	25	200	22.9	350.00	509.09
4	3.00	50	100	60.0	113.64	413.64
5	30.00	50	800	40.0	227.27	362.73
6	5.00	400	800	12.5	250.00	286.36
7	2.00	200	600	5.0	350.00	318.18
8	1.00	0	100	10.0	190.91	76.36
9	20.00	50	300	80.0	304.55	76.36
10	6.50	150	300	43.3	477.27	63.64
				Total minimum flow rate		354.4

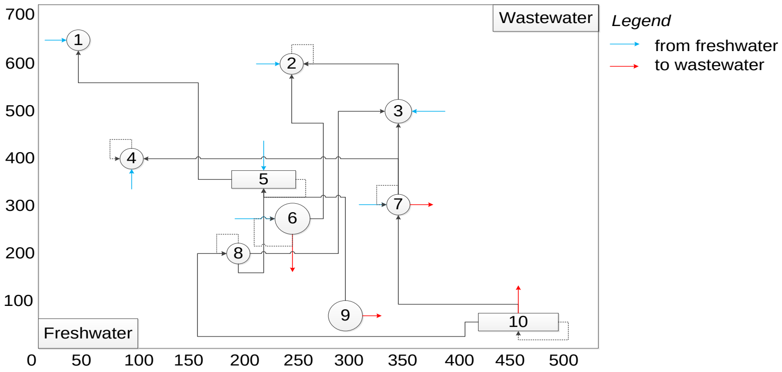

Figure 1: Case 1 - Integrated Water Network

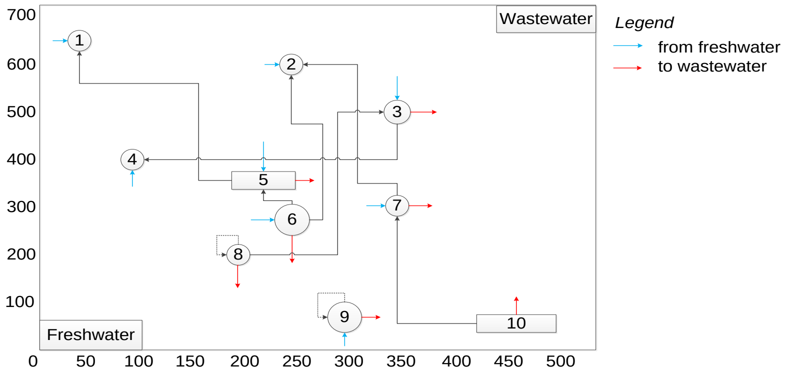

Figure 2: Case 2 - Integrated Water Network with Reduced Complexity

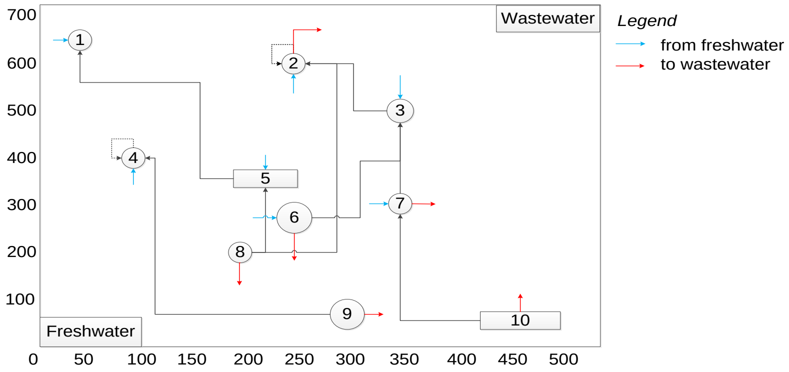

Figure 3: Case 3 - The Decomposed Water Network

Table 2: Case 1 - Flowrates of Integrated Water Network

	Sink 1	Sink 2	Sink 3	Sink 4	Sink 5	Sink 6	Sink 7	Sink 8	Sink 9	Sink 10	Wastewater
Fresh water	10.00	26.26	32.00	17.14	23.18	18.00	40.53	-	-	-	-
Source 1	-	-	-	-	-	-	-	-	-	-	-
Source 2	-	10.10	-	-	-	-	-	-	-	-	-
Source 3	-	12.31	-	-	-	-	-	-	-	-	-
Source 4	-	-	-	5.71	-	-	-	-	-	-	-
Source 5	36.36	-	-	-	0.45	-	-	-	-	-	-
Source 6	-	-	-	-	-	0.10	-	-	-	-	79.90
Source 7	-	-	34.92	4.29	-	-	0.26	-	-	-	34.72
Source 8	-	21.90	25.08	-	17.4	-	-	0.85	-	-	-
Source 9	-	-	-	-	5.00	-	-	-	-	-	40.00
Source 10	-	-	-	-	-	-	8.35	4.15	-	0.76	12.50

Table 3: Case 2 - Flowrates of Integrated Water Network with reduced complexity

	Sink 1	Sink 2	Sink 3	Sink 4	Sink 5	Sink 6	Sink 7	Sink 8	Sink 9	Sink 10	Wastewater
Fresh water	10.00	33.33	34.31	22.86	23.64	30	35.69	-	3.75	-	-
Source 1	-	-	-	-	-	-	-	-	-	-	-
Source 2	-	-	-	-	-	3.03	-	-	-	-	-
Source 3	-	-	-	10.00	-	-	-	-	-	-	21
Source 4	-	-	-	-	-	-	-	-	-	-	-
Source 5	36.36	-	-	-	-	-	-	-	-	-	12.86
Source 6	-	-	-	-	10.00	-	-	-	-	-	76.97
Source 7	-	44.31	-	-	-	-	-	-	-	-	30.83
Source 8	-	-	39.00	-	-	-	-	4.33	-	-	0.67
Source 9	-	-	-	-	-	-	-	-	1.25	-	38.75
Source 10	-	-	-	-	-	-	12.50	-	-	-	12.5

Table 4: Case 3 - Flowrates of Decomposed Water Network

	Sink 1	**Sink 2**	**Sink 3**	**Sink 4**	**Sink 5**	**Sink 6**	**Sink 7**	**Sink 8**	**Sink 9**	**Sink 10**	**Wastewater**
Fresh water	10.00	26.26	32.00	17.86	23.63	20.00	40.00	-	-	-	-
Source 1	-	-	-	-	-	-	-	-	-	-	-
Source 2	-	10.1	-	-	-	-	-	-	-	-	1.42
Source 3	-	12.31	-	-	-	-	-	-	-	-	-
Source 4	-	-	-	5	-	-	-	-	-	-	-
Source 5	36.36	-	-	-	-	-	-	-	-	-	-
Source 6	-	-	20.00	-	-	-	-	-	-	-	80.00
Source 7	-	-	40.00	-	-	-	-	-	-	-	30.83
Source 8	-	20.48	-	-	22.86	-	-	-	-	-	5.00
Source 9	-	-	-	5.00	-	-	-	-	-	-	40.00
Source 10	-	-	-	-	-	-	12.50	-	-	-	12.50

Table 5: Comparison between different models

	Case 1	**Case 2**	**Case 3**
Freshwater, F_{FW} (t/y)	167	194	170
Piping Cost, *CC* ($)	3,297,283	3,714,628	3,515,060
Operating Cost, *OC* ($/y)	2,673,909	3,097,227	2,716,098
Number of pipelines, *NP*	28	24	23
Total Annual Cost, *TAC* ($/y)	3,435,582	3,955,306	3,528,077

*The cost of supplying freshwater and treated wastewater is estimated to be 1 $/t/h.

As shown in Table 5, the network in cases 2 and 3 have less piping connections as compared to that in case 1. By setting upper boundaries for the number of pipelines and piping length, the network is divided into subsystems as according to Figure 3. By dividing the network into subsystems, the disturbances arises within the processing units remain within the subsystems; hence, easier controllability can be achieved to amend the disturbances, Note however that the costs of these cases are higher than that of case 1. In other words, the reduced complexity is compensated with higher cost. The piping and total annual costs of Model 3 is higher than those in case 1 by 6.6 % and 2.7 % respectively. The increase in operating cost of Model 3 is resulted by 16 % increment in freshwater and wastewater flowrates. However, the piping cost, total annual cost and freshwater flowrate of case 3 is significantly lower than those in case 2. On the other hand, by

4. Conclusions

This paper presented a superstructural model of water network that emphasises on reduced network complexity, based on the number of piping connections and piping length. Future research work can be carried out to develop clustering approach in reducing the complexity of water network, integration of regeneration unit, as simultaneous heat and water recovery.

Nomenclature

<u>*Sets*</u>		<u>*Parameter*</u>	
SRi	Set of process sources	*AF*	Annualising factor
SKj	Set of process sinks	*AOT*	Annual operating hour
FW	Set of fresh resources	C_{in}^{max}	Maximum inlet concentration
WW	Set of waste disposals	C_{out}^{max}	Maximum outlet concentration
<u>*Variable*</u>		CT_{FW}	Unit cost of fresh resource
$B_{SRi,SKj}$	Binary variable for the existence of piping connection from *SRi* to *SKj*	CT_{WW}	Unit cost of waste discharge
		$D_{SRi,SKj}$	Distance between *SRi* and *SKj*
CC	Capital cost	*IR*	Annual fractional interest rate
$F_{FW,SKj}$	Flowrate from source *FW* to sink *SKj*	NP^{UB}	Upper bound for number of pipeline
F_{SKj}	Flowrate required at sink *SKj*	PL^{UB}	Upper bound for piping length
F_{SRi}	Total flowrate from source *Sri*	q_{FW}	Quality for fresh resource *FW*
$F_{SRi,SKj}$	Flowrate from source *SRi* to sink *SKj*	q_{SKi}	Quality of sink *SKi*
$F_{SRi,WW}$	Flowrate from source *SRi* to sink *WW*	q_{SRi}	Quality of source *SRi*
NP	Total number of pipeline	X_{SKi}	x-coordinate of sink *SKi*

OC	Operating cost	X_{SRi}	x-coordinate of source *SRi*
PL	Total piping length	Y_{Ski}	y-coordinate of sink *SKi*
TAC	Total annual cost	Y_{SRi}	y-coordinate of source *SRi*

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