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A two-stage optimization approach for the synthesis of resource conservation networks involving interception units

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ABSTRACT

This study presents a mathematical optimization model for resource conservation network (RCN) synthesis that includes interception units within the structure of the network. RCNs are the one of the most efficient designs for minimizing fresh water consumption, wastewater generation, and operation cost. Interception units (single pass and partitioning units) are widely accepted industrial application techniques used to reduce network complexity and flow rate targets in RCN. Cost equations relating to the piping and operating costs are added when interception units are designed in an RCN. Then, the problem is formulated as a two-stage optimization model whose objective functions are to minimize freshwater consumption and total annualized cost (TAC). The applicability of the developed model is demonstrated with two case studies. Single pass interception units with a fixed outlet concentration (C_{Rout}) reduced freshwater consumption by 23.16% and 46.3%, while partitioning units reduced consumption by 21.69% and 29% respectively, when compared to base systems.

1. Introduction

Water has become a major source of supply in many process industries; for example paper and pulp and chemical industries rely completely on freshwater. Optimization of freshwater consumption is one of the most important objectives of modern process industries. Increases in resource prices and operating costs lead process industries to optimize freshwater consumption while maintaining profitability. As result of improvements in material conservation and recycling/reuse, mass/heat exchange network-based process integration has seen major efficiency gains over the past decades. Process integration technique has emerged as an effective tool in identifying various retrofit alternatives and is defined as a holistic approach to design, modernize, and unify processes (El-Halwagi, 1997, 2006). This approach serves as a more aggressive strategy for pollution prevention than conventional end-of-pipe waste treatment activities (Chen et al., 2011). Process industries are also in search of efficient and less expensive technologies to sustainably design manufacturing processes. Within the framework of process integration, resource conservation network (RCN) activities are cost-effective solutions where materials are recycled/reused within processes without adversely affecting the process performance (Ng et al., 2009b).

Compared to an end-of-pipe wastewater treatment system, process integration approaches involving RCNs are well suited to address various resource conservation alternatives. In most cases, fresh material consumption and waste generation are reduced simultaneously through resource conservation

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Nomenclature

Sets

i	$\{i = 1, 2, 3, 4\ldots$ sources$\mid i$ is a set of process sources$\}$
j	$\{j = 1, 2, 3, 4\ldots$ sinks$\mid j$ is a set of process sinks$\}$

Variables

W_{RE}	flow rate of a single pass interception inlet stream
W_{REG}	regenerated (purified) flow rate of single pass interception
W_{FW}	total freshwater flow rate
$W_{FW,SKj}$	required fresh water flow rate for sink j
$W_{REG,SKj}$	regenerated (purified) flow rate required by sink j
$W_{SRi,SKj}$	reuse/recycle flow rate from source i to sink j
$W_{SRi,RE}$	regenerated flow rate from source i
$W_{SRi,WW}$	wastewater flow rate from source i
W_{Rin}	inlet flow rate of partitioning interception unit
W_p	purified stream flow rate of partitioning interception unit
W_{RJ}	reject flow rate of partitioning interception unit
C_{Rin}	inlet stream concentration of partitioning interception unit
C_P	purified stream concentration of partitioning interception unit
C_{RJ}	reject stream concentration of partitioning interception unit
$W_{RJ,SKj}$	reject flow rate of partitioning interception unit from sinks j
TAC	total annual cost
OC	operating cost
PC	piping cost
$B_{SRi,SKj}$	binary variable indicating the existence of connection between sinks and sources

Parameters

$W_{SR,i}$	limiting flow rate of source i
$C_{SR,i}$	limiting concentration of source i
$W_{SK,j}$	limiting flow rate of sink j
$C_{SK,j}$	limiting concentration of sink j
C_{SKj}^{min}	maximum admissible concentration of sink j
C_{SKj}^{max}	minimum admissible concentration of sink j
C_{Rout}	outlet concentration of regenerated stream
α	liquid recovery factor
RR	removal ratio
AWT	annual working time
L	unit cost of waste water
M	unit cost of freshwater
N	unit cost of regenerated water
U	upper bound of reuse/recycle flow rate for both the interception units
D	individual distance between sinks and sources
v	stream flow rate velocity
ρ	water density
AF	annualizing factor
p	fractional interest rate
q	number of years

activities (Dunn and El-Halwagi, 2003; Smith, 2005). To establish network alternatives, recent trends have minimized water consumption through process integration, recycling, reuse, and regeneration (Saif et al., 2008). Implementing material reuse/recycling in RCN synthesis can reduce water consumption and waste generation while embedding various process elements within the structure of the RCN.

Wang and Smith (1994) developed a model which involves all possible configurations for water regeneration–recycling and regeneration-reuse. Yang et al. (2000) proposed a wastewater reuse network in the form of a mathematical program, such that the model was aimed at minimizing wastewater when multiple pollutants are contained in the water stream. Apart from the reuse network, systematic methods have been developed to reduce water usage and effluent generation simultaneously based on pinch analysis (Bai et al., 2007; El-Halwagi et al., 2003; Feng and Seider, 2001; Foo et al., 2006; Hallale, 2002; Prakash and Shenoy, 2005) and mathematical modeling (Savelski and Bagajewicz, 2001; Jeżowski et al., 2003; Tan and Cruz, 2004; Tan et al., 2007a; Tsai and Chang, 2001). However, mathematical modeling offers significant advantages over graphical techniques in handling cost equations, limited piping considerations, forbidden or compulsory matches between certain processes, and process uncertainty (Chen et al., 2011; Tan et al., 2008).

When the detailed synthesis of an RCN is achieved, process sources are partially treated by interception units or regeneration processes in order to further reduce target flowrates after the potential for water recovery through direct reuse/recycling is exhausted (Chen et al., 2011; Ng et al., 2009a). Interception units are a viable technology in process industries. Interception units are classified into two general categories: single pass and partitioning units. Both interception units are classified as fixed outlet quality (C_{Rout}) and removal ratio (RR) type (Foo and Manan, 2006; Hallale and Liu, 2001; Ng et al., 2009a). In the single pass unit, the inlet stream and outlet streams have same flow rates ($F_{Rin} = F_{Rout}$). On the other hand, partitioning units accept a feed water stream and produce two outlet streams of different quality: the purified stream and the reject stream. The purified stream is of higher quality than the feed water stream, while the reject stream is of lower quality than the feed. Partitioning units encompass membrane-based processes (e.g. reverse osmosis), flotation processes, and gravity settling systems (Tan et al., 2010).

Several reports have studied the incorporation of interception units in RCNs (Bai et al., 2007; Bandyopadhyay and Cormos, 2008; Kuo and Smith, 1998; Ng et al., 2008). Takama et al. (1980) suggested water regeneration-based mathematical optimization, which involves the development of a superstructure accounting for all possible configurations of reuse and regeneration. Bagajewicz and Savelski (2001) considered linear programming (LP) and mixed integer linear programming (MILP) models to synthesize optimal water superstructure. This heuristic approach was suggested to guide the placement of regeneration units. Ng et al. (2007) proposed a numerical targeting procedure to locate the minimum regeneration flow rate for both fixed flow rate and fixed load problems. Tan et al. (2010) employed a graphical pinch analysis approach to target the minimum flow rate of a partitioning water pretreatment system. However, they did not address the total annual cost (TAC) of pretreatment units in the water network. Ng et al. (2009a) proposed an automated targeting technique to determine RCN targets involving interception units. However, the automated targeting technique fails to account for TAC for the partitioning interception unit. Recent studies have focused on heuristic approaches and targeting flowrates to determine the minimum freshwater flow rate. Studies addressing TAC for fixed outlet quality and removal ratio (RR) based RCN of interception units are scarce. Our work allows calculation of TAC for the interception units. We formulated detailed optimization models for RCN synthesis while satisfying all process constraints; we will also synthesize various resource conservation alternatives.

This study focuses on RCN synthesis that incorporates interception units with fixed outlet quality and RR-based superstructure which embeds all possible process elements. The RCN is the modification of the superstructure given by (Tan et al., 2009) and has several units of freshwater, wastewater, regenerated water, etc. It provides network alternatives which provide meaningful connectivity between the sources and sink streams. The RCN also considers off limit and compulsory matches with specific piping connections. Therefore, the mathematical programming model is formulated as a two-stage optimization model. In the first stage, freshwater is minimized for the RCN, incorporating interception units in the sink–source superstructure. In this case, a mathematical model is formulated for LP and quadratic programming (QP) for single pass and partitioning interception units, respectively. Correspondingly, freshwater is included as a new constraint in the second stage, where TAC is minimized. This mathematical model is formulated as a MILP and a mixed integer quadratic programming (MIQP) for single pass and partitioning interception units, respectively. This paper consists of three parts. In the first part, a superstructure approach is introduced for designing an optimal RCN. The basic element for the approach is to define the number of recycle/reuse connections between sinks and sources and freshwater and sinks, etc. In second part, for detailed description of superstructure, a connectivity matrix based RCN is developed. Accordingly, an optimization model for RCN is then defined and solved by MILP and MIQP programming method for single pass and partitioning interception units respectively. In the third part, we explore two case studies using the developed model and resultant RCN's feature the minimum amount of freshwater consumption and TAC.

2. Problem statement

In process integration, some special cases focus on material recovery. As a result, resource conservation networks (RCNs) are an alternative for the design of process industries, which address various process elements such as freshwater, recycle/reuse streams, interception units, and wastewater. The synthesized RCN design is identified by heuristics and optimization techniques. Furthermore, optimization of RCNs is characterized by the existence of process units and their interconnections. Implementation of reuse/recycle/interception units can further reduce the RCN. Therefore, the problem statement for the synthesis of RCNs involving recycle/reuse units is as follows.

Fig. 1 illustrates the superstructure (Foo, 2012; Nápoles-Rivera et al., 2010; Parand et al., 2013) model for the reuse/recycle scheme, given a set of process units which has available amount of water to recycle/reuse, designated as sources. Every source flow rate W_{SRi} is characterized by a quality index C_{SRi}, which is considered for recycle/reuse or discharge. On the other hand, we are given a set of resource demand units in a process, which is known as the process sink, or SK = {j = 1, 2, 3, 4,... sinks}. The sinks are the process units that can accept recycle/reuse streams. Every sink, j, requires a feed with flow rate W_{SKj}, and an inlet composition of targeted quality index C_{SKj}. The quality index must satisfy certain bounds on their values. These bounds are described by the allowable constraint as follows:

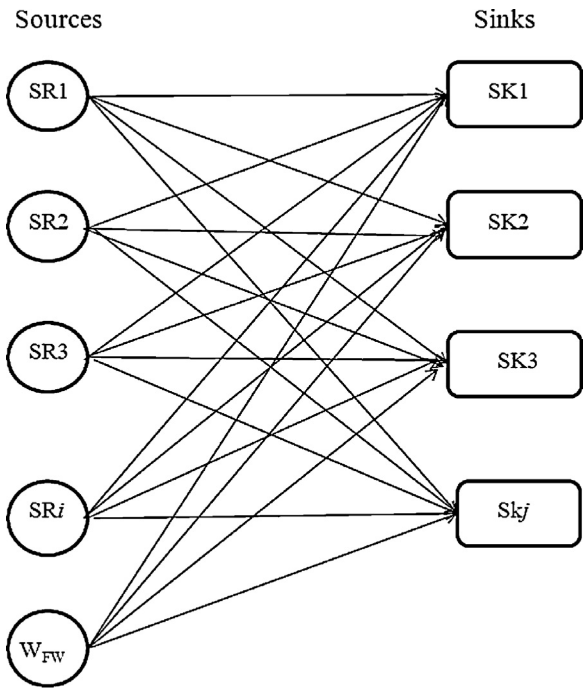


Fig. 1 – Superstructure model for a recycle/reuse network (Foo, 2012; Nápoles-Rivera et al., 2010; Parand et al., 2013).

$$C_{SKj}^{min} \leq C_{SKj} \leq C_{SKj}^{max} \quad (1)$$

where C_{SKj}^{min} and C_{SKj}^{max} are the specified lower and upper limits on the admissible compositions of sink j. It is worth noting that the quality index is the inlet impurity concentration, C_{SKj}, for the concentration based RCN. Thus, for the concentration based RCN the impurity concentration, C_{SKj}, should satisfy the upper and lower bounds. Furthermore, the quality index of an RCN differs significantly from one case to another (Foo, 2012). However, when the process source is inadequate to fulfill the sink requirements, external freshwater is required to satisfy the sinks. Incorporating interception units in RCNs can further reduce feed water consumption and waste generation. Subsequently, a superstructural approach is needed to involve interception units in an RCN.

In this study, we synthesized interception units with a fixed outlet quality and RR-based RCN. As the result, the RCN problem is formulated as an optimization model whose objectives are to minimize freshwater consumption and total annual cost (TAC). Hence, we developed a two-stage optimization model that minimizes feed water consumption and TAC while keeping all process constraints which are equality constraints such as flow rate balance for process sinks and sources, and flow rate balance for interception units and inequality constraints such as impurity constraint for process sinks, and flow rate constraint in piping connections.

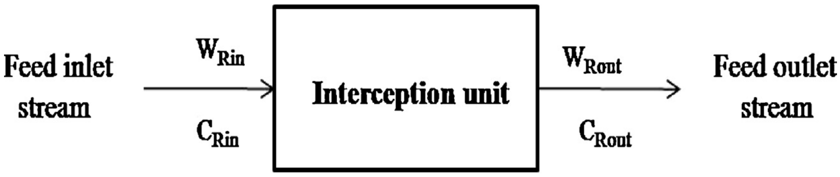


Fig. 2 – Single pass interception unit.

3. Model development

3.1. *Superstructure approach*

A superstructure approach is used to synthesize the RCN while embedding all process elements. The problem is defined as a two-stage optimization approach, so the overall RCN is comprised of two parts. Interception units are classified into two types: a superstructural mathematical model for single pass interception units and partitioning units is presented separately in the following sections.

3.2. *Stage 1: synthesis of RCN for minimum fresh water*

In the first stage, interception units are integrated in a sink–source arrangement to minimize freshwater consumption. The freshwater is considered as a source because sinks are probable units which accept the source. The first stage is formulated as superstructure model consisting of a flow rate balance of sinks, sources, and constraints with all feasible connections between sinks, sources, and interception units.

3.2.1. *Mathematical model for a single pass unit*

The single pass interception unit is designed as a process unit that consists of single input and single output streams, as illustrated in Fig. 2. The focal point of single pass interception unit is to maximize the water recovery and improve water quality from sources. A typical single pass interception unit for improving water quality process is depicted in Fig. 2. In the process, the interception unit draws water from sources at low quality concentration level with corresponding flow rates and discharges the higher quality water (Ng et al., 2009a) and this higher quality water is further utilized by process sinks. Furthermore, the inlet feed stream and outlet stream have equal flow rates, i.e., $W_{Rin} = W_{Rout}$.

To synthesize the RCN for a single pass interception unit, we first constructed a superstructural representation incorporating interception unit with sinks and sources. Fig. 3 illustrates the superstructural design (Foo, 2012) of the single pass interception unit with all the possible relations of source and sinks. Interception units are designed and implemented such that they feature and operate as both sinks and sources. In particular, interception unit is acted as sink when the source of flow rate $W_{SRi,RE}$ passes through the interception unit. As a result, the purified stream that exits the interception unit is further utilized by sinks with flow rate $W_{REG,SKj}$. As shown in Fig. 3, the superstructure allows every possible connection between the process units such as connections between sources and interception unit, interception unit to sink and connection between sources and sinks, which are represented by the flow rate variables $W_{SRi,RE}$, $W_{RE,SKj}$, and $W_{SRi,SKj}$ respectively. The solution of this optimization model provides the optimal flow rate arrangements of the aforementioned variables which are to be employed in the RCN.

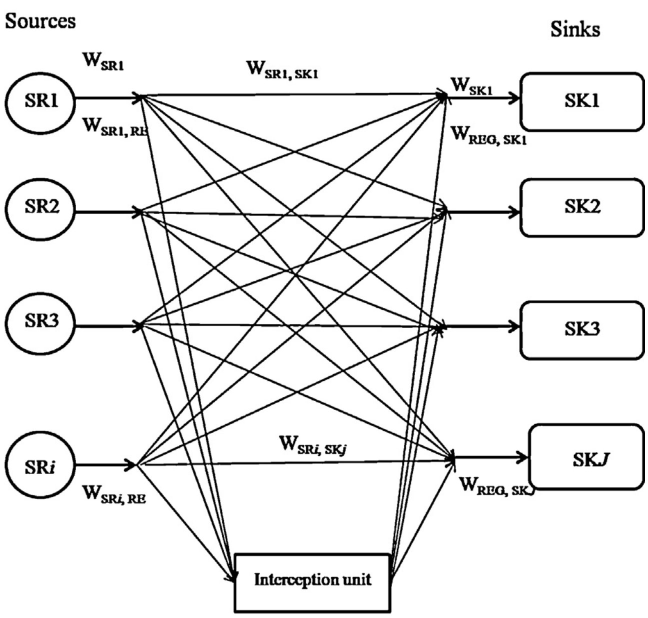


Fig. 3 – Superstructure network for a single pass interception unit (Foo, 2012).

The structure and the information flow rate targets are also significant to the model. Due to the compatibility of the superstructural approach with many possible connections between sinks and sources, a connectivity matrix model-based RCN (Ng et al., 2013) is designed to represent the superstructure. As shown in Fig. 4, a connectivity matrix model is formulated between sinks and sources. The connectivity matrix-based RCN is developed by first reciting the number of sources, sinks, and interception units in the network. Each element has a row and a column in the connectivity matrix network. The rows correspond to sinks, which accept water from sources. The columns correspond to sources, which can be sent to sinks for reuse/recycling. The connectivity matrix also has rows and columns assigned to the freshwater flow rate stream and the wastewater stream. Freshwater is designated as a source while wastewater is designated as a sink.

For a single pass interception unit, each inlet stream has a ($W_{SRi,RE}$) connection with the source while each outlet stream has a ($W_{REG,SKj}$) connection with the sinks. Based on the RCN of single pass interception shown in Fig. 4 and the superstructure model illustrated in Fig. 3, no connections are built between freshwater and wastewater flow rates. Furthermore, no connections are built between the freshwater and the interception unit or between wastewater and the regenerated sources. This fact becomes particularly important because in practice, freshwater is free of any contaminant so that freshwater neither be discharged as effluent nor treated for regeneration to further water recovery. Moreover, it is inherent that the output of interception unit, i.e., regenerated source which is higher quality is further send to process units which accept water to satisfy its requirement rather than discharge as waste. Furthermore, the unused source flow rate by sink is discharged

		W_{SKj} (t/h)	W_{SK1}	W_{SK2}	W_{SK3}	W_{SK4}	W_{RE}	W_{WW}
		C_{SKj} (ppm)	C_{SK1}	C_{SK2}	C_{SK3}	C_{SK4}	C_{RE}	C_{WW}
W_{SRi} (t/h)	C_{SRi} (ppm)	*Sink j* *Source i*	SK1	SK2	SK3	SK4	RE	Wastewater (WW)
W_{FW}	C_{FW}	Fresh Water	$W_{FW,SK1}$	$W_{FW,SK2}$	$W_{FW,SK3}$	$W_{FW,SK4}$		
W_{REG}	C_{REG}	Regenerated water (REG)	$W_{REG,SK1}$	$W_{REG,SK2}$	$W_{REG,SK3}$	$W_{REG,SK4}$		
W_{SR1}	C_{SR1}	SR1	$W_{SR1,SK1}$	$W_{SR1,SK2}$	$W_{SR1,SK3}$	$W_{SR1,SK4}$	$W_{SR1,RE}$	$W_{SR1,WW}$
W_{SR2}	C_{SR2}	SR2	$W_{SR2,SK1}$	$W_{SR2,SK2}$	$W_{SR2,SK3}$	$W_{SR2,SK4}$	$W_{SR2,RE}$	$W_{SR2,WW}$
W_{SR3}	C_{SR3}	SR3	$W_{SR3,SK1}$	$W_{SR3,SK2}$	$W_{SR3,SK3}$	$W_{SR3,SK4}$	$W_{SR3,RE}$	$W_{SR3,WW}$
W_{SR4}	C_{SR4}	SR4	$W_{SR4,SK1}$	$W_{SR4,SK2}$	$W_{SR4,SK3}$	$W_{SR4,SK4}$	$W_{SR4,RE}$	$W_{SR4,WW}$

Fig. 4 – Representation of connectivity matrix model-based RCN for single pass unit (Foo, 2012).

as wastewater. As illustrated in Fig. 4, each element has a flow rate ($W_{SRi,SKj}$) whose value will be resolved by the optimization model.

Next the optimization model is formulated for single pass interception unit. The optimization objective is set to minimize freshwater consumption which is given in Eq. (2), while satisfying all possible processes constraints.

The mathematical model for a single pass interception unit is as follows:

$$\text{Minimize} \quad \textit{Freshwater}\ (WFW) \tag{2}$$

where the total freshwater flow rate is the sum of individual flow rates, which are shown in Fig. 4 as follows:

$$W_{FW} = \sum_{j} W_{FW,SK_j} \tag{3}$$

The following constraints describe the flow rate and impurity balances for sinks and sources:

$$\sum_{i} W_{SR_i,SK_j} + W_{FW,SK_j} + W_{REG,SK_j} = W_{SK_j} \forall j \tag{4}$$

The constraint in Eq. (4) requires that the sinks' flow rate demand is satisfied by various process sources ($W_{SRi,SKj}$), freshwater ($W_{SRi,SKj}$) and the regenerated source ($W_{SRi,RE}$)

$$\sum_{i} W_{SR_i,SK_j} + W_{FW,SK_j} C_{FW} + W_{REG,SK_j} C_{Rout} \leq W_{SK_j} C_{SKj} \forall j \tag{5}$$

Eq. (5) describes sinks that accept water form sources, freshwater, and regenerated sources ($W_{REG,SKj}$) with minimum water quality, where C_{Rout} represents the outlet concentration of the regenerated source and C_{FW} represents the concentration of freshwater.

For a single pass interception unit, the flow rate balance is given as $W_{RE} = W_{REG}$. The superstructure approach for flow rate balance is given as follows:

$$\sum_{i} W_{SR_i,RE} = \sum_{j} W_{REG,SK_j} \tag{6}$$

where $\sum_{j} W_{REG,SK_j}$ the summation of is regenerated source and $\sum_{i} W_{SR_i,RE}$ is the summation of sources to be sent for regeneration.

The flow rate balance for the process source is given as follows:

$$\sum_{i} W_{SR_i,SK_j} + W_{SR_i,RE} + W_{SR_i,WW} = F_{SR_i} \forall i \tag{7}$$

where $\sum_{i} W_{SR_i,SK_j}$ is the summation of flow rate sources allocated to process sinks and $W_{SR_i,WW}$ is the unutilized source flow rate that is discharged as waste water.

All variables in the connectivity matrix of Fig. 4 take non-negative values:

$$(W_{SR_i,SK_j}), (W_{FW,SK_j}), (W_{REG,SK_j}), (W_{SR_i,RE}), (W_{SR_i,WW}) \geq 0 \forall j, i \tag{8}$$

On inspection, constraints (2)–(8) constitute linear programming (LP) when fixed outlet quality is considered.

To illustrate the applicability of the single pass unit model, we considered two case studies with sources and sinks. To further reduce network complexity, we considered a single pass interception unit of fixed outlet quality (C_{Rout}). The objective of the two case studies is to minimize the freshwater in the system while satisfying all process demands.

3.2.2. *Mathematical model for partitioning interception unit*

Fig. 5 illustrates the partitioning interception unit, which accepts the feed water stream with quality (C_{Rin}) and produces two outlet streams of different quality. One stream is known as the purified stream, and is of higher quality (Cp) than the feed water stream. The second stream is known as the reject, and is of lower quality (C_{RJ}) than the feed. Partitioning units include membrane-based processes, gravity settling systems, and flotation processes (Tan et al., 2010). Further in this study it is assumed that no significant flow rate loss, i.e., no material

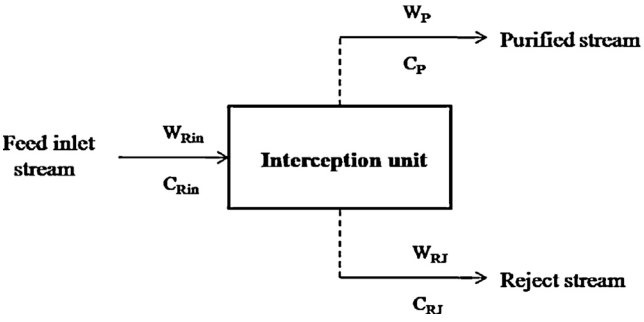


Fig. 5 – Partitioning interception unit.

loss and generation, the overall flow rate balance is given as (Ng et al., 2009a):

$$W_{Rin} = W_P + W_{RJ} \tag{9}$$

where W_{Fin}, W_P, and W_{RJ} are the flowrates of the inlet feed stream, purified stream, and reject stream, respectively.

The overall desired product recovery is given by the recovery factor α, which is defined as the flow rate ratio of the purified stream to the inlet feed stream. This is given as follows:

$$\alpha = \frac{W_P}{W_{Rin}} \tag{10}$$

The component balance of partitioning unit is given as:

$$W_{Rin}C_{Rin} = W_P C_P + W_{RJ}C_{RJ} \tag{11}$$

where C_{Fin}, C_P, and C_{RJ} are the concentrations of inlet feed stream, purified stream, and reject stream, respectively.

Fig. 6 illustrates the superstructural model for partitioning interception units in which sinks and sources are constructed. The partitioning unit acts as both sink and source. The inlet feed stream of the interception unit acts as the sink when the source of flow rate $W_{SRi,RE}$ is supplied. Correspondingly, the higher and lower quality of the regenerated source from the outlet of the interception unit leads to further recycling/reuse in the process sinks with flow rates $W_{REG,SKj}$ and $W_{RJ,SKj}$. The relationships constructed by flow rate variables $W_{SRi,RE}$,

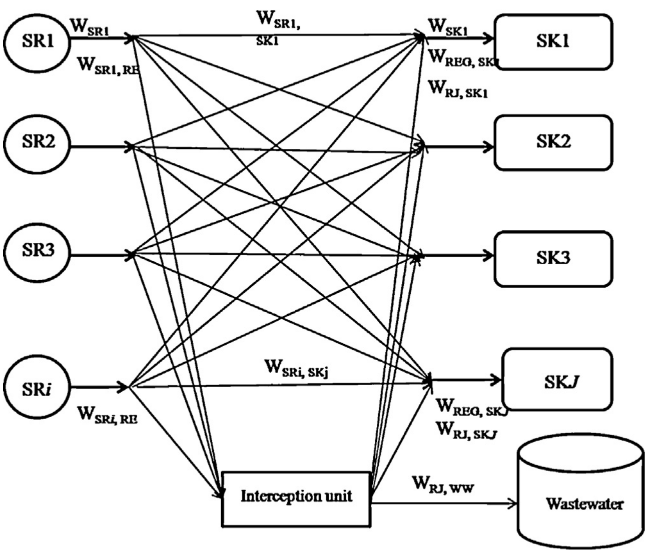


Fig. 6 – Superstructure network for a partitioning interception unit.

$W_{RE,SKj}$, $W_{RJ,SKj}$, and $W_{SRi,SKj}$ are acquired through the optimization model. If the regenerator reject is not directed for further recycling/reuse, the reject flow is discharged as wastewater.

A simplified model formulation approach takes the form of a connectivity matrix model based RCN, with the revised form shown in Fig. 7. The connectivity matrix consists of rows and columns, with rows representing sinks and columns representing sources. Freshwater and wastewater streams are added to the connectivity matrix to accommodate the sinks and source streams. The freshwater only flows to sinks, and never to sources or interception units. This is because when the process source stream is inadequate to feed sinks, an external freshwater source may satisfy the requirement of sinks. Subsequently, the unwanted source flowrates are sent only to waste discharge. For the partitioning unit, two output streams, the purified stream and the reject steam, are produced. The purified stream is not mixed with the reject stream, since the purpose of the partitioning unit is to serve the inlet feed stream to create a purified stream and a reject stream.

We have formulated the optimization model for the partitioning unit. The optimization objective is to minimize freshwater consumption while assuring all possible process constraints.

The mathematical model for the partitioning interception unit is as follows:

$$\text{Minimize } \textit{Freshwater}\ (W_{FW}) \tag{12}$$

The total freshwater flowrate is the sum of individual flow rate. This is represented in Fig. 7 as follows:

$$W_{FW} = \sum_j W_{FW,SK_j} \tag{13}$$

The following constraints describe the flowrate and impurity balances for sinks and sources:

$$\sum_i W_{SR_i,SK_j} + W_{FW,SK_j} + W_{REG,SK_j} + W_{RJ,SK_j} = W_{SK_j} \forall j \tag{14}$$

where the constraint in Eq. (4) requires that the sink flow rate demand is satisfied by various process sources ($W_{SRi,SKj}$), freshwater ($W_{SRi,SKj}$), regenerated source ($W_{REG,SKj}$), and reject stream ($W_{RJ,SKj}$).

$$\sum_i W_{SR_i,SK_j} C_{SR_i} + W_{FW,SK_j} C_{FW} + W_{REG,SK_j} C_{REG} + W_{RJ,SK_j} C_{RJ} = W_{SK_j} C_{SKj} \forall j \tag{15}$$

Eq. (15) describes sinks that accept water from sources, freshwater, and regenerated source ($W_{REG,SKj}$) with minimum water quality. Here, C_{RJ} represents the concentration of the reject stream, C_{Rout} represents the outlet concentration of the regenerated source, and C_{FW} represents the concentration of freshwater.

The liquid recovery factor α is given for a partitioning interception unit in the revised form shown in Eq. (16). The

		W_{SKj} (t/h)	W_{SK1}	W_{SK2}	W_{SK3}	W_{SK4}	W_{RE}	W_{WW}
		C_{SKj} (ppm)	C_{SK1}	C_{SK2}	C_{SK3}	C_{SK4}	C_{RE}	C_{WW}
W_{SRi} (t/h)	C_{SRi} (ppm)	*Sink j* *Source i*	SK1	SK2	SK3	SK4	RE	Wastewater (WW)
W_{FW}	C_{FW}	Fresh Water	$W_{FW,SK1}$	$W_{FW,SK2}$	$W_{FW,SK3}$	$W_{FW,SK4}$		
W_{RJ}	C_{RJ}	Reject water (RJ)	$W_{RJ,SK1}$	$W_{RJ,SK2}$	$W_{RJ,SK3}$	$W_{RJ,SK4}$		$W_{RJ,WW}$
W_{REG}	C_{REG}	Regenerated water (REG)	$W_{REG,SK1}$	$W_{REG,SK2}$	$W_{REG,SK3}$	$W_{REG,SK4}$		
W_{SR1}	C_{SR1}	SR1	$W_{SR1,SK1}$	$W_{SR1,SK2}$	$W_{SR1,SK3}$	$W_{SR1,SK4}$	$W_{SR1,RE}$	$W_{SR1,WW}$
W_{SR2}	C_{SR2}	SR2	$W_{SR2,SK1}$	$W_{SR2,SK2}$	$W_{SR2,SK3}$	$W_{SR2,SK4}$	$W_{SR2,RE}$	$W_{SR2,WW}$
W_{SR3}	C_{SR3}	SR3	$W_{SR3,SK1}$	$W_{SR3,SK2}$	$W_{SR3,SK3}$	$W_{SR3,SK4}$	$W_{SR3,RE}$	$W_{SR3,WW}$
W_{SR4}	C_{SR4}	SR4	$W_{SR4,SK1}$	$W_{SR4,SK2}$	$W_{SR4,SK3}$	$W_{SR4,SK4}$	$W_{SR4,RE}$	$W_{SR4,WW}$

Fig. 7 – Representation of connectivity matrix model based RCN for partitioning unit.

superstructure approach for liquid recovery factor is given as follows:

$$\alpha = \frac{\sum_j (W_{REG,SK_j})}{\sum_i W_{SR_i,RE}} \tag{16}$$

Here, the summation of $\sum_j (W_{REG,SK_j})$ is regenerated source or the purified stream and $\sum_i W_{SR_i,RE}$ is the summation of sources to be sent for regeneration.

The flow rate balance for the process source is given as follows:

$$\sum_j W_{SR_i,SK_j} + W_{SR_i,RE} \le W_{SR_i} \forall i \tag{17}$$

where $\sum_j W_{SR_i,SK_j}$ is the summation of flow rate sources allocated to process sinks and $W_{SR_i,RE}$ is the flow rate of the regenerator or interception unit sent for purification.

The removal ratio (RR) is optimized using the concentration balance. RR is defined as the proportion of feed water stream entering the interception unit that exists in the reject stream.

$$(1 - RR)\sum_i W_{SR_i,RE} C_{SR_i} = C_{REG} \sum_j (W_{REG,SK_j}) \tag{18}$$

$$(RR)\sum_i W_{SR_i,RE} C_{SR_i} = C_{RJ}(1-\alpha)\sum_j (W_{SR_i,RE}) \tag{19}$$

All variables in the connectivity matrix of Fig. 7 take non-negative values.

$$(W_{SR_i,SK_j}), (W_{FW,SK_j}), (W_{REG,SK_j}), (W_{SR_i,RE}), (W_{SR_i,WW}), (W_{RJ,SK_j}) \ge 0 \forall j, i \tag{20}$$

Constraints (12)–(20) constitute quadratic programming (QP) when α and RR are considered.

We solved two case studies to illustrate the proposed partitioning interception unit approach. As has been previously mentioned, when detailed design of RCN is achieved, process sources are interloped with partitioning interception unit to further reduce the flow rate targets. In this study, partitioning interception optimizes α and RR to achieve the minimum freshwater consumption and TAC. Furthermore, the concentrations of purified feed stream (C_{REG}) and the reject stream concentration (C_{RJ}) are obtained for any value of α and RR. The objective of the two case studies is to minimize the freshwater use of the system while satisfying all process demands.

3.3. *Stage 2: synthesis of RCN for minimizing total annual cost (TAC)*

Stage 1 dealt with the synthesis of RCN configurations for freshwater minimization. The task of stage 2 is to determine the total annual cost for the interception units. However, the second stage is solved in combination with first stage to minimize the TAC. The result of second stage determines the optimal flow rate targets of RCN, number of piping connections between sinks and sources, TAC, operating cost, piping cost, etc. The constraints specified in the second stage consists of freshwater, regenerated water, recycle/reuse flow rates, etc. Therefore, we synthesized an alternative RCN which encompasses all possible elements. In contrast, an alternative RCN is also obtained if the optimization models can also preclude any specified forbidden or compulsory connections between sinks and sources. In other words, additional constraints can be added to impose the connections between sinks and sources as active or not. It is worth noting that the reasons for considering forbidden connections include prohibition of low quality water for reuse/recycle, a large distance between process sources and sinks, etc. On the other hand, the reasons for imposing compulsory connection is to fulfill the sink requirement, and for safety considerations, etc. In this regard, an alternative RCN design is obtained when additional constraints are added to impose the forbidden or compulsory connections between sinks and sources. However, in this study, no additional constrains are added to impose forbidden or compulsory connections. Therefore, to address the RCN of interception units, we have introduced equations relating to the operating cost and capital cost to design variables through the stage 2 formulation.

The superstructure for interception units in resource conversion networks (RCNs) is shown in Figs. 3 and 6. In order to synthesize an alternative RCN, we used an alternative objective function. Thus, the superstructural approach can determine the piping cost of an RCN which shows the connections between sink and source streams. The estimated operating cost, piping cost, and annual working time are used to calculate the total annual cost (TAC) of the RCN.

The mathematical model for interception units is formulated and the objective function is presented as follows:

$$Min\,TAC = OC\,(AWT) + PC \tag{21}$$

Eq. (21) is the objective function which minimizes the total annual cost (TAC) for the superstructural approach. Where OC is operating cost, AWT is the annual working time and PC is the piping cost.

The operating cost is given as the cost of freshwater, wastewater, and regenerated water. The particular cost terms are the product of freshwater, wastewater, and regenerated flow rates with their unit costs. Hence, Eq. (22) is given as:

$$OC = LW_{WW} + MW_{FW} + N\sum_{i} W_{REG,i} \tag{22}$$

where W_{FW}, and $W_{REG,i}$ represent the freshwater and regenerated flowrates of sources i respectively. L, M, and N reflect the unit costs of wastewater, freshwater, and regenerated water, respectively.

Here, we consider a material regeneration/recycle/reuse problem where the piping cost is the second term to be minimized in the objective function. The binary variable B_{SR_i,SK_j} may be used to determine the presence of connections between the sources and sinks as follows:

$$W_{SR_i,SK_j} \le U \times B_{SR_i,SK_j} \tag{23}$$

where B_{SR_i,SK_j} is the binary variable. It takes the value of 1 when there is a connection between SR_i and SK_j; otherwise it takes the value of 0. U is the arbitrary large number. For Eq. (23), the binary term will be unity when the W_{SR_i,SK_j} takes the nonzero value, i. If $W_{SR_i,SK_j} = 0$ then the binary variable is zero. In this way, the connections between sources and sinks are obtained when the optimization design is performed.

The capital cost of the RCN is generally contributed by piping cost (PC) in Eq. (21), which is adapted from (Kim and Smith, 2004) and shown in Eq. (24). Carbon steel pipes (USD), with the cost parameters of $p = 7200$ and $q = 250$ (CE plant index 318.3) are considered for piping connections. Here, it is assumed that the stream flow rate velocity is $\nu = 1\,\text{ms}^{-1}$ and that the water density is $\rho = 1000\,\text{kg mt}^{-3}$ in pipes throughout the study (Chew et al., 2008; Kim and Smith, 2004).

$$PC = D\left(a\frac{W_{SR_i,SK_j}}{3600\rho\upsilon} + bB_{SR_i,SK_j}\right) \times AF \tag{24}$$

where D is the individual distance between water sinks and water sources. AF is the annualizing factor used to annualize the piping cost, which is defined as follows:

$$AF = \frac{p(1+p)^q}{(1+p)^q - 1} \tag{25}$$

where p is the fractional annual interest rate and q is the number of years considered. The piping cost is annualized over 5 years, with an interest rate of 5%.

Eqs. (21)–(25) depict the mathematical model for total annualized cost. The optimization design problem is formulated through mixed integer linear programming (MILP) and mixed integer quadratic programming (MIQP) to minimize the total annualized cost subject to technical and flexibility constraints. The constraints (22)–(25) constitute a MILP problem for which an optimal solution is readily attained.

The objective of stage 2 is to synthesize an alternative resource conservation network (RCN). The objective function is set to minimize the total annual cost. We have clearly exhibited equations formulating the optimization model. Two case studies are solved to illustrate the proposed model and are described methodically to effectively illustrate synthesized RCNs. Furthermore, the case studies are meant to distinguish the RCNs of stage 1 and stage 2.

4. Results and discussions

Two case studies are discussed to illustrate the proposed method for the synthesis of a resource conservation network (RCN) involving interception units within the network. The first case study depicts paper production, where freshwater is highly used in paper mills. The second describes eco-industrial parks (EIPs), which are essential to establish a water exchange network between the plants installed within them.

4.1. *Case study 1 (paper mill)*

We will illustrate a typical paper mill that processes old newspapers and magazines to produce paper (Tan et al., 2007b). In this case study, a typical paper mill with processing of old newspapers and magazines to produce paper are utilized for illustration (Tan et al., 2007b; Ng et al., 2009a). As shown in Fig. 8, the paper mill is a complex water network with flowrates of freshwater consumption of 1989.06 ton h^{-1} and wastewater generation of 1680.3 ton h^{-1}, respectively. In the paper mill, the objective of pulpers is to blend the old news papers under the dilution water and chemicals to form pulp slurry called stock. The paper machine receives 986.52 ton h^{-1} of freshwater via two streams namely pressing section and forming section to remove the debris. Water leaving from the pressing section

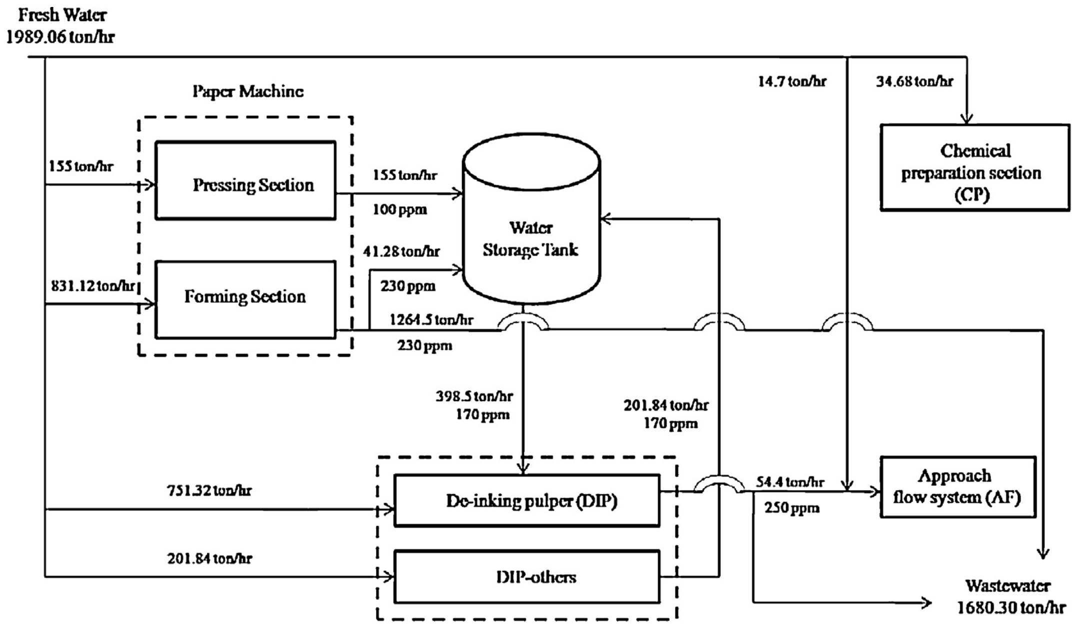


Fig. 8 – A preliminary water network for the paper mill case study (Tan et al., 2007b; Ng et al., 2009a).

and part of water from forming section is mixed with recycled water from the De-inking pulper (DIP) section especially DIP others are sent to storage tank.

From the main stock printing ink is removed via DIP section, freshwater of 751.32 ton h^{-1} and reused water of 398.5 ton h^{-1} of storage tank flowrates are fed to DIP. Moreover, freshwater flowrate of 201.84 ton h^{-1} is fed to other DIP processes. In order to dilute the stock, water leaving from the DIP with flowrate of 54 ton h^{-1} is mixed with freshwater flowrate of 14.7 ton h^{-1} is fed to approach flow system (AF). Before the chemicals sent to DIP section for ink removal, freshwater with flowrate of 34.68 ton h^{-1} is fed to chemical precipitation unit (CP) to dilute de-inking chemicals. Remarkably, the paper mill is served with freshwater consumption of flowrate 1989.06 ton h^{-1}.

On the other hand, prior the discharge of wastewater with flowrate of 1680.3 ton h^{-1} which is accumulated from the part of paper machine section and DIP units are directed to the effluent treatment plant. For the paper mill case study, Table 1 summarizes the pertinent data for the water sinks and water sources. Water sinks refer to the water using process where water source refer to water leaving from sinks. The total suspended solids (TSS) were determined to be the most important water quality factor (Aviso et al., 2010; Ng et al., 2009a; Tan et al., 2007b).

Water use can be intercepted with interception units to increase water recovery in the RCN. In the paper mill case study, a dissolved air flotation (DAF) tank is frequently used as a water purification technique to reduce TSS from process streams. The minimum achievable outlet concentration $C_{Rout,min}$ is 30 ppm for a DAF tank (Tan et al., 2007b), which we have used in this example.

4.1.1. *Single pass interception unit*

The first type of RCN scheme is illustrated with single pass interception. The paper mill case study is revisited to illustrate the application of the superstructural approach in placing a single pass interception unit with fixed outlet quality C_{Rout} = 30 ppm in the RCN. The limiting data is provided in Table 1.

Process sources are interloped with interception units to reduce freshwater and wastewater flow rates. In this example, single pass single pass interception units with a fixed outlet quality of C_{Rout} = 30 ppm are used. Sequential optimization is considered for the synthesis of an alternative RCN. To compare the minimum water flow rate targets obtained from previous works (Aviso et al., 2010; Ng et al., 2009a; Tan et al., 2007b), we used a two-stage optimization model. The linear programming (LP) model was first solved using the objective function in Eq. (1) to minimize the total freshwater flow rate, subject to constraints in Eqs. (3)–(8). Next, mixed integer linear programming (MILP) was also solved to minimize the total annualized cost (TAC) using Eq. (20), subject to constraints in Eqs. (3)–(8) and, Eqs. (21)–(24).

Solving Eq. (2) subject to the constraint in Eqs. (3)–(8) yields an optimal RCN shown in Fig. 9. Both the freshwater and wastewater targets are determined to be 308.76 t/h and 0 t/h respectively. The optimal RCN design for case study 1 is a threshold water networks that attains zero discharge, as shown in Fig. 9a. As shown in Fig. 9a, the

Table 1 – Pertinent data for water sinks and water sources for the paper mill case study (Aviso et al., 2010; Ng et al., 2009a; Tan et al., 2007b).

Water sinks	Flow rate (t/h), W_{skj}	Concentration (ppm)	Water sources	Flow rate (t/h), W_{SRj}	Concentration (ppm)
Pressing section	155.40	20	Pressing section	155.40	100
Forming section	831.12	80	Forming section	1305.78	230
De-inking pulper	201.84	100	De-inking pulper	201.84	170
DIP-others	1149.84	200	DIP-others	469.80	250
Chemical precipitation	34.68	20			
Approach flow system	68.70	200			

(a)

		W_{SKj} (t/h)	190.08	831.12	201.84	1218.54	667.24	0
		C_{SKj} (ppm)	20	80	100	200	30	0
W_{SRi} (t/h)	C_{SRi} (ppm)	*Sink j* / *Source i*	SK1	SK2	SK3	SK4	RE	Wastewater (WW)
308.76	0	Freshwater	152.06	157.7				
667.24	30	Regenerated water (REG)		382.58	54.89	229.76		
155.40	100	SR1	38.02		117.38			
201.84	170	SR2		201.84				
1305.78	230	SR3		89.99	29.55	518.97	667.24	
469.80	250	SR4				469.80		

(b)

		W_{SKj} (t/h)	190.08	831.12	201.84	1218.54	667.24	0
		C_{SKj} (ppm)	20	80	100	200	30	0
W_{SRi} (t/h)	C_{SRi} (ppm)	*Sink j* / *Source i*	SK1	SK2	SK3	SK4	RE	Wastewater (WW)
308.76	0	Fresh Water	190.08	99.55	19.12			
667.24	30	Regenerated water (REG)		481.21		186.03		
155.40	100	SR1			155.40			
201.84	170	SR2		92.11	27.31		82.40	
1305.78	230	SR3		158.23		1000.0	147.54	
469.80	250	SR4				32.5	437.29	

Fig. 9 – Optimal RCN designs incorporating a single pass unit (Case Study 1). (a) RCN for stage 1 with a single pass interception unit scheme; (b) RCN for stage 2 with a single pass interception unit scheme.

optimization results indicate that the total minimum regenerated water is 667.24 t/h. 667.24 t/h of the regeneration feed (W_{RE}) is sent for purification in the single pass interception unit. An outlet concentration (C_{Rout}) of 30 ppm produces a purified regenerated flow rate (W_{REG}) of 667.24 t/h, which is distributed to sinks. The regenerator is subjected to further reuse/recycle in the water network. This corresponds to a 23.16% reduction in the freshwater water and threshold zero discharge when compared to the base systems. Based on the single pass interception unit results, the minimum outlet concentration (C_{Rout}) must have caused threshold zero discharge.

Having dealt with RCN flow rates determined in the stage 1 (FW and WW) as parameters, we solved the stage 2 model to determine the total annual cost of the RCN for single pass interception units. The following assumptions are made for the paper mill case study. (1) The concentration of freshwater is zero. (2) An equal Manhattan distance of $D = 30$ m is maintained between water demands, water sources, and fresh water supply. (3) The capital cost for the RCN is annualized over 5 years, assuming a 5% fixed interest rate. (4) The annual operating time is 8000 h. (5) for operating cost calculations, unit costs of freshwater and regenerated water are assumed at $1/ton and $0.001/ton. The above assumptions are used to illustrate the TAC of an RCN configuration with a single pass interception unit. The model for stage 2 (MILP formulation) entails 88 continuous variables, 20 binary variables, and 82 constraints. It takes 0.05 CPU s to solve the model and the total annual cost is 2.475 million $/year. Fig. 9b shows the optimal RCN configuration incorporating a single pass interception unit. It is observed that minimum fresh water and wastewater flow rates are determined as 308.76 t/h and 0 t/h, respectively, which is identical for the case in stage 1. This indicates that multiple degenerate solutions exist for this problem, in which more than one RCN design achieves the same minimum water flow rates but different network design. It is worth noting that for concentration based RCN, the degenerate solution is defined when the objective value and solution does not change but there exists an alternative RCN. This model emphasizes the reduction of connections and piping costs in the industries, which has led designers to create a new industrial outline to minimize these costs.

Table 2 – Distinctive illustration of water flows (Aviso et al., 2010).

Water required	Flow rate (t/h), W_{skj}	Concentration (ppm)	Water available	Flow rate (t/h), W_{SRj}	Concentration (ppm)
Plant 1	4.16	10	Plant 1	4.16	100
Plant 2	0.833	100	Plant 2	0.833	250
Plant 3	3.33	20	Plant 3	2.08	80
Plant 4	2.5	50	Plant 4	4.16	200

4.1.2. *Partitioning interception unit*

The second type of RCN scheme addressed in this work is a separation process which uses a partitioning interception unit in the network. Water sources are fed to the partitioning interception unit, which then discharges a lower concentration product stream and a higher concentration reject stream. The lower concentration feed stream is used for recycling/reuse to satisfy process demands. The higher concentration reject stream is discharged as effluent or for further possible recycle/reuse within the network. To precisely design a partitioning interception unit, we introduced the liquid recovery factor α and the removal ratio (RR). Partitioning interception units synthesize an RCN that minimizes fresh water use and TAC. There is considerable flexibility for liquid recovery factor α and RR. The proposed partitioning model optimizes α and RR to identify the minimum freshwater and TAC.

We revisited the paper mill case study to illustrate the application of the partitioning interception unit. Table 1 shows the operating data for the paper mill case study. A sequential optimization is carried to out illustrate the partitioning unit model. The quadratic programming (QP) model was first solved using the objective function in Eq. (12) to minimize the total freshwater flow rate, subject to constraints in Eqs. (13)–(20). Next, mixed integer quadratic programming (MIQP) was used to minimize the total annualized cost (TAC) using Eq. (21), subject to constraints in Eqs. (13)–(20) and Eqs. (22)–(25).

The objective function in Eq. (12) is solved subject to constraints in Eqs. (13)–(20), which yields an optimal RCN, as shown in Fig. 10. Freshwater and wastewater flow rates were 314.65 t/h and 5.89 t/h, respectively. These decreased significantly when using an optimized partitioning interception unit with a liquid recovery factor of $\alpha = 0.99$ and a removal ratio of 0.92. At these values, the model is optimized for minimum freshwater consumption. Liquid recovery factor and RR are less than unity, which is useful for industry processes. As shown in Fig. 10a, water from the two lowest quality sources (sources 3 and 4) with concentrations of 230 and 250 ppm, respectively, are purified by the partitioning unit. The maximum flow rate of the interception unit is utilized by the lean stream. Demands 1 and 2 consume 189.91 t/h and 222.05 t/h respectively, while demands 3 and 4 consume 94.11 t/h and 77.83 t/h, respectively. Demand 2 consumed combinations of freshwater (314.65 t/h), lean stream flow rate of (222.05 t/h), and reuse/recycle connections (294.4 t/h) from sources 2 and 3 to satisfy its requirement. The rich stream flow rate (5.89 t/h) from the partitioning unit is not directed for recycle/reuse operations but is instead discharged as effluent.

It is significant to note that when the liquid recovery factor increases, there is a decrease in freshwater consumption, waste generation, and regenerator capacity. Based on the partitioning interception unit results, maximum liquid recovery α and 90% removal rate have minimum flow rate targets. The comparison shows that a 21.69% reduction in freshwater requirement is achieved through a partitioning interception unit.

Next, the MIQP model is optimized by minimizing the total annual cost using Eq. (21), subject to constraints in Eqs. (13)–(20) and Eqs. (22)–(25). The model for stage 2 (MIQP formulation) entails 96 continuous variables, 24 binary variables, and 92 constraints. It takes 0.09 CPUs to solve the model, and the total annual cost is 2.58 million $/year. Fig. 10 shows that TAC optimization for a partitioning interception unit is approximated at 2.58 million $/year, with freshwater and wastewater flowrates at 314.64 and 5.89 t/h, respectively. The same freshwater and wastewater flowrates are obtained for both stages, despite different optimization models. However, the individual recycle/reuse flow rates differ between the demands, and sources between the two stages also differ. This is unsurprising, as similar optimization models with different objective function are likely to have more than one RCN.

Analyzing the optimal solutions shown in Fig. 10b, the two lowest quality sources, 3 and 4, are purified by the interception unit. The lean stream used the maximum flow rate of 583.1 t/h and later, all the sinks consume the lean stream flow rate. The freshwater flow rate of 314.64 t/h was consumed by demand 2 in both stages. In stage 2, demand 2 combines the flow rates of freshwater (314.64 t/h), the lean stream (248.31 t/h), and source 3 (268.16 t/h). The rich stream flow rate is similar in both stages. The water from the rich stream is directly sent to wastewater disposal without any recycle/reuse operations.

Results from earlier work using the water cascade analysis (WCA; Foo et al., 2006) show the minimum flow rates of freshwater and wastewater to be 848 t/h and 539 t/h respectively. Based on pinch analysis, minimum freshwater and wastewater flow rates of the water network with regeneration were 401 t/h ad 92.52 t/h respectively (Tan et al., 2007b). Using the generic automated targeted technique (Ng et al., 2009a) for RCNs with interception units in a removal ratio (RR) mode, the minimum freshwater and wastewater flowrates were 320 t/h and 12.21 t/h, respectively. We achieved a 23% (308.76 t/h) reduction in freshwater requirement and threshold zero discharge through single pass interception unit while a partitioning interception unit offer a reduction of 21.69% (314.65 t/h) and 52% (5.89 t/h), respectively.

Furthermore, another representation for ease of RCN design takes the form of schematic diagram. The RCN which is represented in Figs. 9 and 10 is used to illustrate the schematic representation which is shown in Figs. 13 and 14 and vice versa. In this study, the RCNs obtained for both single pass and partitioning interception unit shown in Figs. 9 and 10 with the revised schematic form is illustrated in Figs. 13 and 14 for both the stages.

4.2. *Case study 2 (EIP)*

This case study is adopted from (Aviso et al., 2010). Table 2 shows the distinctive illustration of water flow for sinks and sources. An EIP considering four plants with stream flow rate targets and concentration consisting of the required flow rate of water and concentration of water, available flow rate of water and concentration of water for each plant given in

(a)

		W_{SKj} (t/h)	190.08	831.12	201.84	1218.54	589.81	5.89
		C_{SKj} (ppm)	20	80	100	200	246	22625
W_{SRi} (t/h)	C_{SRi} (ppm)	*Sink j* *Source i*	SK1	SK2	SK3	SK4	RE	Wastewater (WW)
314.65	0	Fresh Water		314.65				
5.89	22625	Reject water (RJ)						5.89
583.91	21	Regenerated water (REG)	189.91	222.05	94.11	77.83		
155.40	100	SR1				155.40		
201.84	170	SR2	0.16	93.95	107.72			
1305.78	230	SR3		200.45		985.30	120.01	
469.80	250	SR4					469.80	

(b)

		W_{SKj} (t/h)	190.08	831.12	201.84	1218.54	589	5.89
		C_{SKj} (ppm)	20	80	100	200	246	22625
W_{SRi} (t/h)	C_{SRi} (ppm)	*Sink j* *Source i*	SK1	SK2	SK3	SK4	RE	Wastewater (WW)
314.64	0	Fresh Water		314.64				
5.89	22625	Reject water (RJ)						5.89
583.1	21	Regenerated water (REG)	189.51	248.31	124.58	20.14		
155.40	100	SR1				155.40		
201.84	170	SR2	0.56			201.84		
1305.78	230	SR3		268.16	77.25	841.15	118.64	
469.80	250	SR4					469.80	

Fig. 10 – Optimal RCN designs incorporating a partitioning unit (Case Study 1). (a) RCN for stage 1 with a partitioning interception unit scheme; (b) RCN for stage 2 with a partitioning interception unit scheme.

Table 2. Further, the sources and sinks segregate a water exchange network between the plants contained within them. Eco-industrial parks (EIP) are designed to minimize resource consumption and waste generation by establishing a water exchange network between plants (Aviso et al., 2010). To further decrease consumption, interception units are used with a hub. This example is used to illustrate single pass and partitioning interception units working with an interception utility hub. We used a two-stage optimization model. The LP and QP for single and partitioning unit models were first solved using the objective function in Eq. (1) to minimize the total freshwater flow rate. Next, MILP and MIQP models were solved to minimize the total annualized cost (TAC) of the RCN.

4.2.1. *Single pass interception unit*

We illustrated the first scenario RCN scheme with a single pass interception unit. The EIP case study is revisited to illustrate the application involving single pass interception units with a fixed outlet quality $C_{Rout} = 30$ ppm. The flow rates and concentrations of the entire system are provided in Table 2. The total freshwater and wastewater flow rates without any recycling are 10.83 t/h and 11.25 t/h, respectively. In the absence of an interception hub, the freshwater consumption and wastewater generation of the system are reduced to 7.55 t/h and 7.97 t/h, respectively, when recycle/reuse operations are considered.

The objective function in Eq. (2) is solved, subject to constraints in Eqs. (3)–(8), which yields an optimal RCN, as illustrated in Fig. 11. Freshwater and wastewater flow rates were 3.887 t/h and 4.29 t/h, respectively. These decreased significantly when an optimized single pass interception unit with a fixed outlet quality of $C_{Rout} = 30$ ppm is used. Freshwater and wastewater flow rates increase with the outlet concentration. On the other hand, smaller values of C_{Rout} decreased with the freshwater and wastewater flow rates.

(a)

		W_{SKj} (t/h)	4.16	3.33	2.5	0.833	5.111	4.30
		C_{SKj} (ppm)	10	20	50	100	30	208.5
W_{SRi} (t/h)	C_{SRi} (ppm)	*Sink j* / *Source i*	SK1	SK2	SK3	SK4	RE	Wastewater (WW)
3.887	0	Fresh Water	2.77	1.108				
5.11	30	Regenerated water (REG)	1.38	2.225	1.5			
2.08	80	SR1			1.0	0.735	0.35	
4.16	100	SR2					4.16	
4.16	200	SR3					0.59	3.57
0.833	250	SR4				0.097		0.735

(b)

		W_{SKj} (t/h)	4.16	3.33	2.5	0.833	5.111	4.30
		C_{SKj} (ppm)	10	20	50	100	30	208.5
W_{SRi} (t/h)	C_{SRi} (ppm)	*Sink j* / *Source i*	SK1	SK2	SK3	SK4	RE	Wastewater (WW)
3.887	0	Fresh Water	2.775	1.108				
5.11	30	Regenerated water (REG)	1.38	2.225	1.5			
2.08	80	SR1			1.0			1.08
4.16	100	SR2				0.833	0.1108	3.225
4.16	200	SR3					4.166	
0.833	250	SR4					0.833	

Fig. 11 – Optimal RCN designs incorporating a single pass unit (Case Study 2). (a) RCN for stage 1 with a single pass interception unit scheme; (b) RCN for stage 2 with a single pass interception unit scheme.

Analyzing the optimal solutions in Fig. 11a, water savings are observed when a single pass interception unit with outlet concentration of 30 ppm is used. The RCN network design features fewer recycle/reuse connections between sinks and sources. Freshwater and regenerated water with flow rates of 2.77 t/h and 1.38 t/h, respectively, satisfy the requirement of plant 1. Plant 2's requirements are satisfied by consuming 1.108 t/h of freshwater and 2.225 t/h of purified regenerated water. It worth noting that 0.59 t/h of water from plant 3 is sent to a regeneration unit for purification, while the rest of the 3.57 t/h is sent directly to wastewater disposal. Since sources 2 and 3 have no connections with process sinks, the flow rates of 4.16 t/h and 0.59 t/h are sent to the regeneration unit for further purification. Source 4, with a flow rate of 0.097 t/h, is sent to plant 4, while a flow rate of 0.735 t/h at most is sent to wastewater disposal. As shown in Fig. 11a, the optimization results indicate that the total regenerated water is 5.11 t/h. Hence, 5.11 t/h of the regeneration feed (W_{RE})

Table 3 – Comparison of flow rate target for two case studies with the base studies.

	Case study 1 (paper mill)				Case study 2 (EIP)		
	Base studies		Current study		Base study	Current study	
	Tan et al. (2007b)	Ng et al. (2009a)	Single pass unit	Partitioning unit	Aviso et al. (2010)	Single pass unit	Partitioning unit
Freshwater flow rate (t/h)	401.82	320.97	308.76	314.65	7.55	3.887	5.15
Wastewater flow rate (t/h)	92.52	12.21	0	5.89	7.97	4.30	5.57
Regenerated flow rate (t/h)	620.27	604.1	667.24	589.81	*n.a.*	5.11	9.28
Purified stream flow rate (t/h)	620.27	591.62	667.24	583.91	*n.a.*	5.11	3.71
Reject stream flow rate (t/h)	*n.a.*	12.21	*n.a.*	5.89	*n.a.*	*n.a.*	5.57

(a)

		W_{SKj} (t/h)	4.16	3.33	2.5	0.833	9.28	5.57
		C_{SKj} (ppm)	10	20	50	100	153.8	230.76
W_{SRi} (t/h)	C_{SRi} (ppm)	*Sink j* / *Source i*	SK1	SK2	SK3	SK4	RE	Wastewater (WW)
5.15	0	Fresh Water	3.08	2.07				
5.57	230.76	Reject water (RJ)						5.57
3.71	38.4	Regenerated water (REG)	1.08	0.825	1.805			
2.08	80	SR1		0.436	0.69		0.952	
4.16	100	SR2				0.833	3.33	
4.16	200	SR3					4.166	
0.833	250	SR4					0.833	

(b)

		W_{SKj} (t/h)	4.16	3.33	2.5	0.833	9.28	5.57
		C_{SKj} (ppm)	10	20	50	100	153.8	230.76
W_{SRi} (t/h)	C_{SRi} (ppm)	*Sink j* / *Source i*	SK1	SK2	SK3	SK4	RE	Wastewater (WW)
5.15	0	Fresh Water	3.08	1.6	0.47			
5.57	230.76	Reject water (RJ)						5.57
3.71	38.4	Regenerated water (REG)	1.08	1.733	0.897			
2.08	80	SR1			1.1308		0.952	
4.16	100	SR2				0.833	3.33	
4.16	200	SR3					4.166	
0.833	250	SR4					0.833	

Fig. 12 – Optimal RCN designs incorporating a partitioning unit (Case Study 2). (a) RCN for stage 1 with a partitioning interception unit scheme; (b) RCN for stage 2 with a partitioning interception unit scheme.

is sent for purification in the single pass interception unit. An outlet concentration (C_{Rout}) of 30 ppm produces a purified regenerated flow rate (W_{REG}) of 5.11 t/h, which is distributed to the plants to satisfy their requirements. The main reason for having lower recycle/reuse connections between process sinks and sources in this scenario is that the interception unit allows all possible connections between the sinks and sources to satisfy its requirements.

Stage 1 minimizes freshwater and wastewater generation, while stage 2 calculates the TAC of an RCN involving a single pass interception unit. The following assumptions are made for the EIP case study. (1) The concentration of freshwater is zero. (2) An equal Manhattan distance of $D = 100$ m is maintained between all water plants and the interception unit. (3) We assume a 5% fixed interest rate, while the capital cost for RCN is annualized over 5 years. (4) The annual operating time of the entire system is 8000 h. (5) for operating cost calculations, unit costs of freshwater and regenerated water are $1/ton and $0.001/ton.

Next, the MILP model is optimized by minimizing total annual cost using Eq. (21), subject to constraints in Eqs. (3)–(8) and Eqs. (22)–(25). The model for stage 2 (MILP formulation) entails 88 continuous variables, 20 binary variables, and 82 constraints. It takes 0.05 CPU s to solve the model and the total annual cost is 1.58 million $/year. Fig. 11b shows that the optimization results of TAC for a partitioning interception unit are 1.58 million $/year, with freshwater and wastewater flow rates at 3.887 and 4.30 t/h, respectively. The freshwater and wastewater targets are in similar to stage 1, even though the RCN details differ. The connection details of purified regenerated water and freshwater are similar for stages 1 and 2. Part of source 1's flow rate (1.0 t/h) is consumed by plant 3, with combination of purified regenerated water to satisfy its requirement, while 1.08 t/h is sent directly to waste discharge. 0.833 t/h from source 2 is consumed by plant 4, while the flow rate of 3.225 t/h is sent directly to wastewater disposal. There are only two possible connections between sinks and sources (from plant 1 to plant 3 and plant 2 to plant 4). These

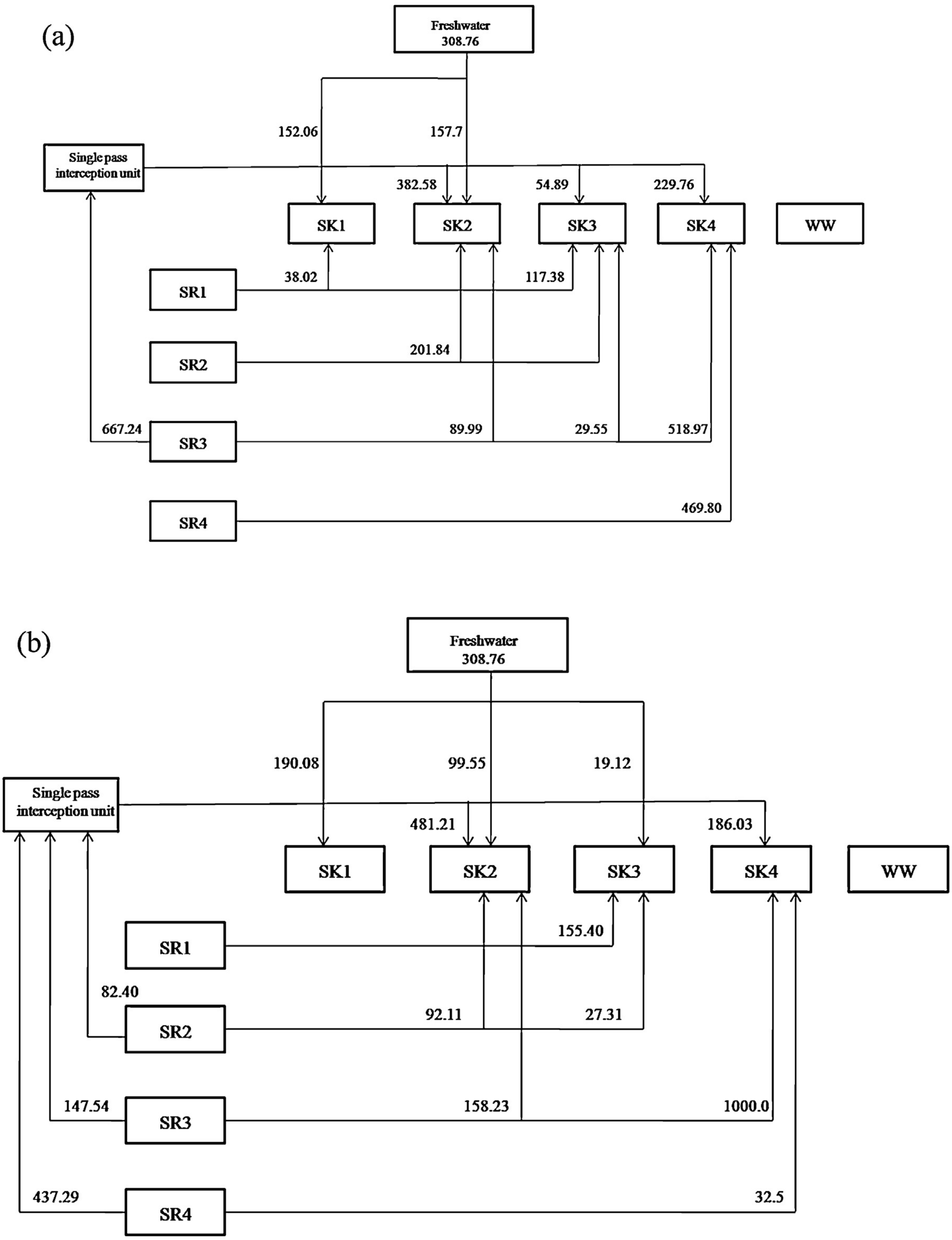


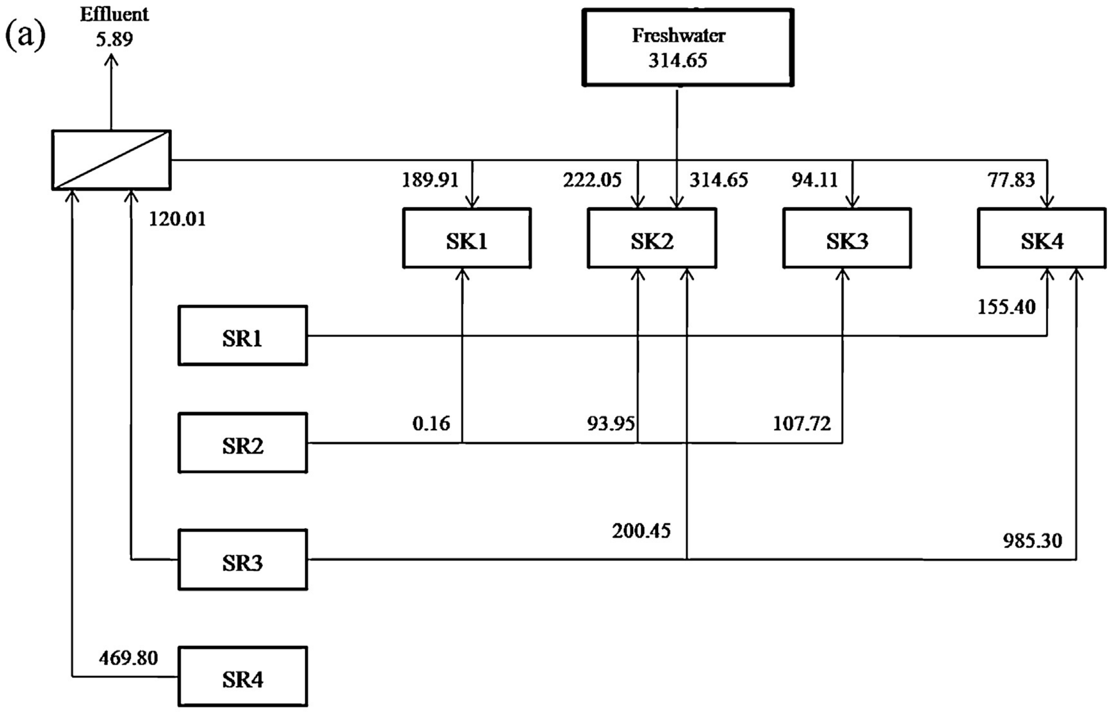
Fig. 13 – Optimal RCN network configuration in Schematic form for single pass interception unit: Case study 1 (All flow rates are given in t/h of water, unless reported otherwise.). (a) Schematic form for single pass unit – stage 1(minimum freshwater): Case study 1; (b) Schematic form for single pass unit – stage 2 (minimum TAC): Case study 1.

contrasts indicate that the purified regenerated flow rate and the freshwater flow rate satisfied the requirement of sinks.

4.2.2. *Partitioning interception unit*

Using the same case study as above, a partitioning interception unit is considered as a utility hub. We used a partitioning interception unit with a liquid recovery ratio of $\alpha = 0.5$ and a removal ratio (RR) of 0.9. Solving Eq. (12) with constraints of Eqs. (13)–(20) yields an optimal RCN, as shown in Fig. 12. The freshwater and wastewater flowrates were 5.15 and 5.57 t/h, respectively. The significant decrease in flow rates is due to the installation of a partitioning interception unit with a flow rate of 9.28 t/h. In this scenario, plants 1 and 2 utilize all the freshwater, while plants 3 and 4 end up with zero flow rates.

As shown in Fig. 12a, the two lowest quality sources 3 and 4, with concentrations of 200 and 250 ppm, are purified by the partitioning interception unit. Subsequently, the lean stream of high quality produced from the partitioning unit is later consumed by plant 1 (1.08 t/h), plant 2 (0.825 t/h), and plant 3 (1.805 t/h). The low-quality reject stream of 5.57 t/h is sent



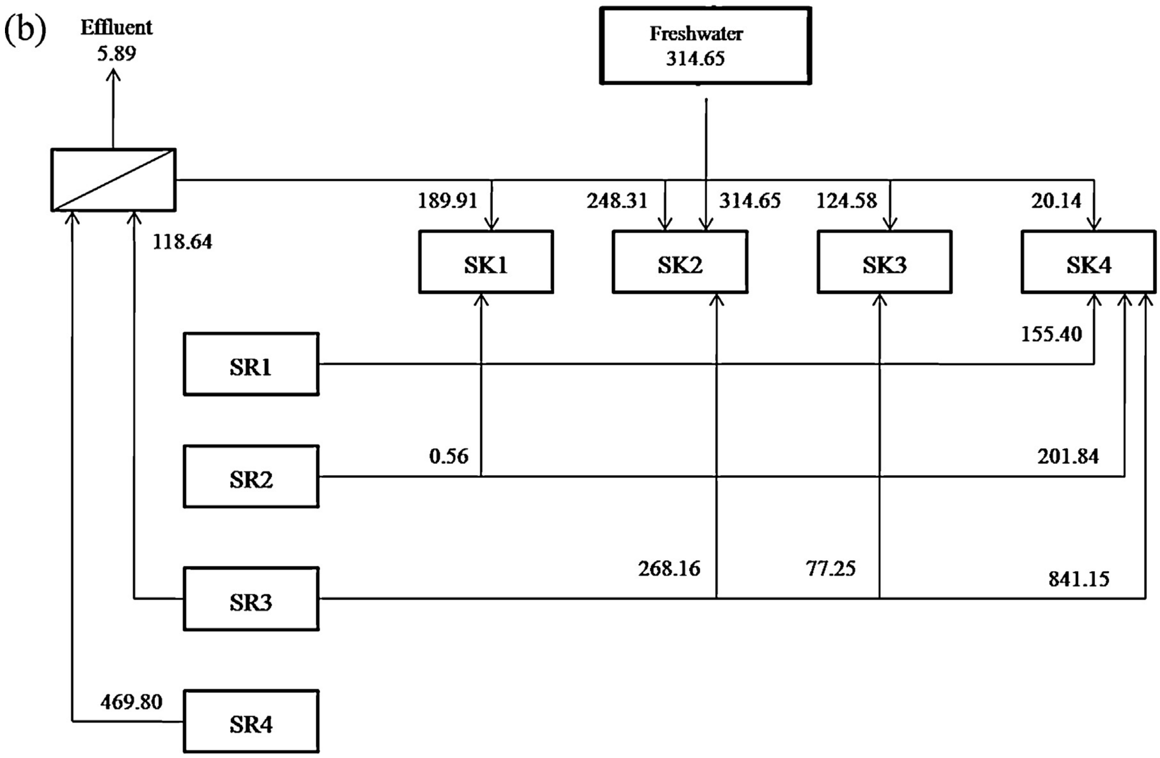


Fig. 14 – Optimal RCN network configuration in Schematic form for partitioning interception unit: Case study 1 (All flow rates are given in t/h of water, unless reported otherwise.). (a) Schematic form for partitioning unit – stage 1(minimum freshwater): Case study 1; (b) Schematic form for partitioning unit – stage 2 (minimum TAC): Case study 1.

directly to wastewater disposal. Plant 2 uses combinations of freshwater (2.07 t/h), purified water (0.825 t/h), and water from source 1 (0.436 t/h) to fulfill its requirements.

Next, the MIQP model is also solved using the objective function in Eq. (21), subject to constraints in Eqs. (13)–(20) and Eqs. (22)–(25). The model for stage 2 (MIQP formulation) entails 96 continuous variables, 24 binary variables, and 92 constraints. It takes 0.08 CPUs to solve the model and the total annual cost is 2.071 million $/year. As illustrated in Fig. 12b, the optimization results of TAC for a partitioning interception unit are approximated at 2.071 million $/year, with freshwater and wastewater flowrates at 5.15 and 5.57 t/h, respectively. The same freshwater and wastewater flowrates are obtained for both stages when the different optimization models are considered. However, the RCN design differs between stages 1 and 2. These contrasts indicate that different optimal solutions exist for the same optimization model.

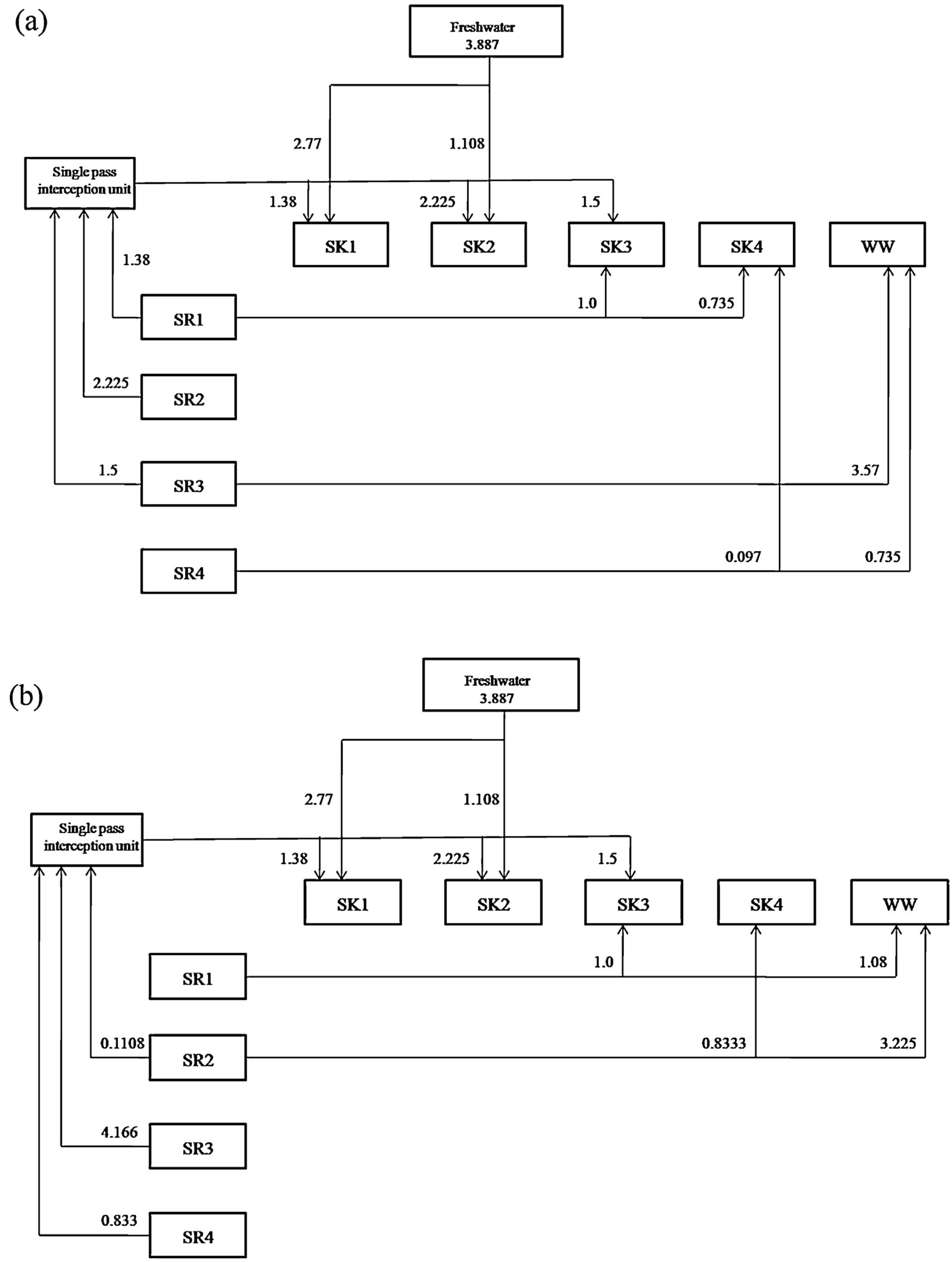


Fig. 15 – Optimal RCN network configuration in Schematic form for single pass interception unit: Case study 2 (All flow rates are given in t/h of water, unless reported otherwise.). (a) Schematic form for single pass unit – stage 1(minimum freshwater): Case study 2; (b) Schematic form for single pass unit – stage 2 (minimum TAC): Case study 2.

Inspecting optimal solutions in Fig. 12b, all four sources with their corresponding flow rates are purified by the interception unit. The interception unit produces a lean stream with a flow rate of 3.71 t/h and a rich stream with a flow rate of 5.57 t/h. All the sinks consume the lean stream flow rate. The freshwater flow rate of 5.15 t/h is consumed by plants 1, 2, and 3. In the stage 2, plant 3 uses flow rates from freshwater (0.47 t/h), lean stream (0.897 t/h), and source 1 (1.1308 t/h). The rich stream flow rate of stage 2 is similar to that of stage 1. The rich stream with a flow rate of (5.57 t/h) is directly sent to wastewater disposal.

Furthermore, an alternative representation of RCN is appears as schematic representation. In this regard, the RCNs obtained for case study 2 considering both single pass and partitioning interception unit shown in Figs. 11 and 12 as an

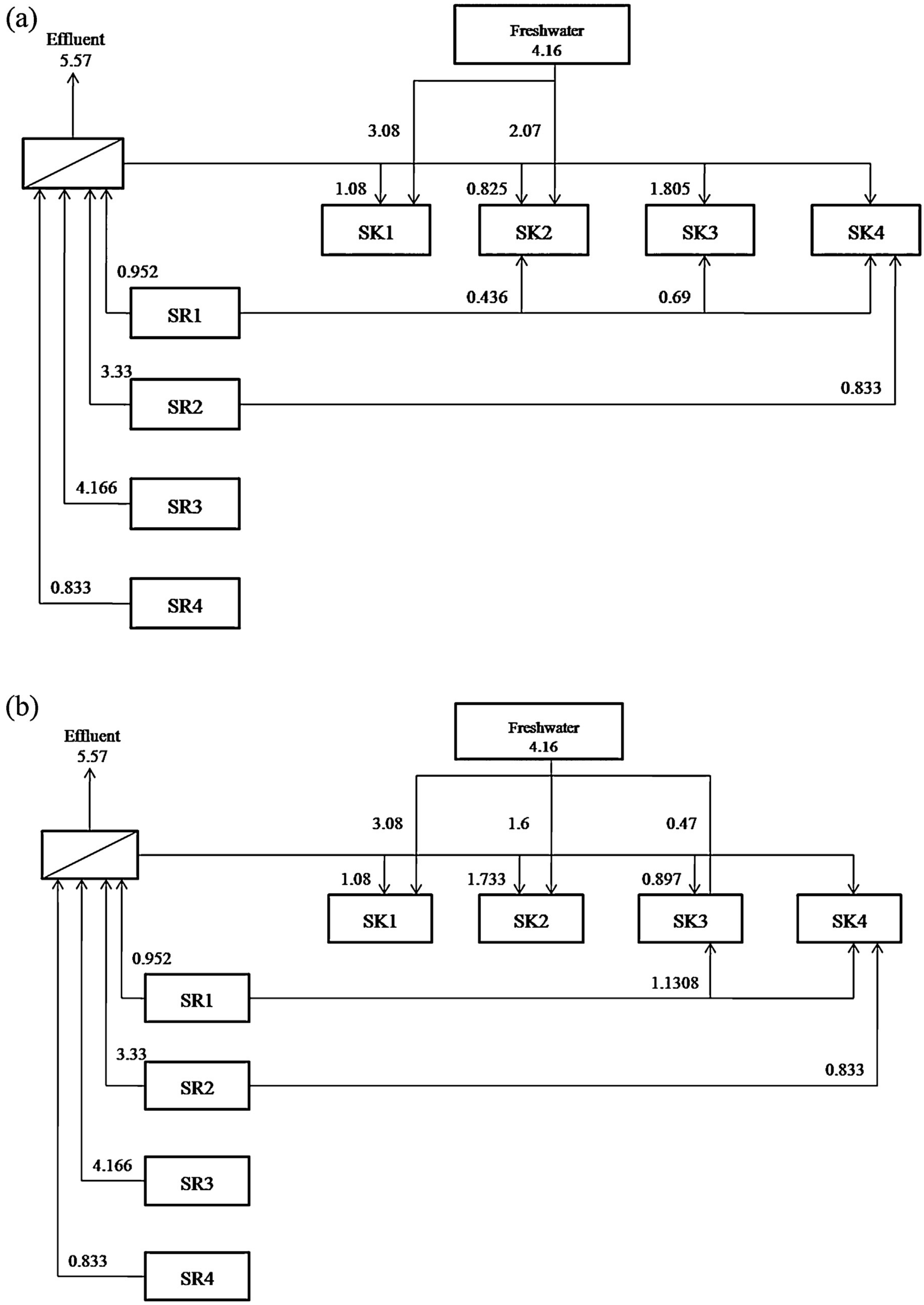


Fig. 16 – Optimal RCN network configuration in Schematic form for partitioning interception unit: Case study 2 (All flow rates are given in t/h of water, unless reported otherwise.). (a) Schematic form for partitioning unit – stage 1(minimum freshwater): Case study 2; (b) Schematic form for partitioning unit – stage 2 (minimum TAC): Case study 2.

Table 4 – Comparison of cost optimal solutions through Total Annual Cost minimization for single pass and partitioning interception units using base studies.

	Case study 1 (paper mill)				Case study 2 (EIP)		
	Base studies		Current study		Base study	Current study	
	Tan et al. (2007b)	Ng et al. (2009a)	Single pass unit	Partitioning unit	Aviso et al. (2010)	Single pass unit	Partitioning unit
Total annual cost (TAC) million $/year	*n.a.*	*n.a.*	2.475	2.58	*n.a.*	1.58	2.071
Annual operating cost (AOC) million $/year	*n.a.*	2.572	2.469	2.56	*n.a.*	1.57	2.062
Piping cost (PC) $	*n.a.*	*n.a.*	52,627	75,127	*n.a.*	37,510	37,500
Operating cost (OC) $/h	*n.a.*	*n.a.*	309.38	321.11	*n.a.*	196.7	257.8

alternative, a schematic form is illustrated in Figs. 15 and 16 for both the stages.

4.3. *Summary of the two case studies*

We designed a water network involving interception units with sinks and sources. In this study two literature examples are solved to illustrate the proposed approach. The resulting MILP and MIQP optimization models are solved using the branch and solver in the commercial optimization LINGO, extended version of 14.0, developed by LINDO systems. LINGO is simple and comprehensive tool for solving linear and nonlinear models, and the results would be better than other existing optimization solvers. The optimization models are solved using standard desktop with an Intel core 3 530 CPU, 2.93 GHz processor. Table 3 summarizes the results of minimum flow rate target results for both the case studies. The comparison shows that a 23% (308.76 t/h) and 46% (3.88 t/h) reduction in freshwater requirement is achieved though single pass interception unit and partitioning interception unit offers a reduction of 21.69% (314.65 t/h) and 29% (5.11 t/h) respectively. The single pass interception unit in the two case studies has negligible flow rate loss, indicating that the inlet flow rates of 665.24 t/h and 5.11 t/h are regenerated and the purified streams of 665.24 t/h and 5.11 t/h are sent to sinks. On the other hand, with a partitioning unit, the regenerated flow rates of 589.81 t/h and 9.28 t/h are partitioned into reject portions of 5.89 t/h and 5.571 t/h, respectively, which are discharged as waste. While the purified stream portions of 583.91 t/h and 3.71 t/h are sent for further recycling in the network. The optimization results tabulated in Table 4 shows the minimum cost elements of RCN for both single pass and partitioning interception units. It observed that in both the case studies single pass interception unit obtained minimum cost when compared to partitioning interception unit. The main reason for having a lower TAC for single pass interception than partitioning unit is that single pass interception unit has obtained minimum flow rate targets. In general, for RCN based concentration systems when the TAC of RCN increases with increased minimum flow rate targets. Therefore, this study has also shown that TAC of RCN increases with increased flow rate targets. Furthermore, it is worth noting that in this study, the annual operating cost (AOC) of single pass interception unit is reduced to 4.3% when compared base study while the AOC of partitioning interception unit reduced to 0.4%. Therefore, the single pass interception unit achieved the minimum freshwater flow rate and TAC than the partitioning interception units. Hence, interception units can provided significant flow rate savings and further intensify the water network.

5. Conclusion

We present two interception unit schemes in this paper. In the single pass interception unit, inlet and outlet stream have same flow rates with negligible flow rate loss. The partitioning interception unit produces two streams, a purified stream and reject stream, and both streams can be reused/recycled within the network. The implementation of interception units in RCN improves the flow rate targets of overall water network. We present a two-stage optimization model for synthesis of RCNs involving interception units, and developed a mathematical model for both stages. In the first stage, interception units are integrated in source–sink superstructure and synthesized to minimize freshwater consumption. Subsequently, freshwater is included as a new constraint in the second stage to minimize the TAC. Two literature case studies were solved to illustrate the proposed approach. Results showed that a significant improvement in flow rate targets can be achieved by incorporating interception units. We propose a superstructural representation of a single pass interception unit and a partitioning interception unit in this study. Through appropriate integration of these two interception units into the two base systems, flow rate targets of the single pass unit and can be decreased by nearly 23% and 46%, respectively than the partitioning unit.

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