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# Synthesis and Optimisation of Total Water Network via Material Flow Cost Accounting (MFCA)-Based Approach

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Material flow cost accounting (MFCA)-based approach which incorporated prioritisation concept of waste recovery to synthesise and optimise a total water network is presented in this work. Based on the proposed approach, an optimal total water network with minimum total operating cost (TOC) which includes the hidden cost of each discharged stream can be synthesised. To illustrate the proposed approach, a case study, integrated sago starch processing plant with wastewater treatment plant, is presented. In this case study, the multiple treatment units with fixed removal efficiency are considered in the waste treatment system.

## 1. Introduction

In past decades, various process integration techniques were developed for water recovery network to determine minimum fresh water and wastewater targets as well as minimum operating cost of a network. These techniques included insight-based techniques (pinch analysis) and mathematical-based optimisation approaches (Foo, 2009). Wang and Smith (1994) presented limiting water profile and composite curve to determine minimum freshwater and wastewater targets. Later, limiting composite curve was extended to determine number of regeneration and final effluent treatment unit (Kuo and Smith, 1998). Meanwhile, supply and demand composite curves (Dhole et al., 1996) and water surplus diagram (Hallale, 2002) were introduced to locate water targets for fixed load problems. Besides, a rigorous Material Recovery Pinch Diagram was introduced by El-Halwagi et al. (2003) as well as independently by Prakash and Shenoy (2005) to determine minimum water targets for fixed flowrate problems. Source composite curve was then proposed to minimise waste generation (Bandyopadhyay, 2006) and operating cost of the overall process (Shenoy and Bandyopadhyay, 2007). Recently, a pinch-based approach was presented to synthesise a chilled water network with minimum chilled water flowrate (Foo et al., 2014). Apart from above graphical approaches, Manan et al. (2004) introduced Water Cascade Analysis (WCA) to determine minimum water targets for fixed flowrate problems. This approach is then extended by Foo et al. (2007) to locate water targets with multiple fresh water sources. Later, Ng et al. (2008) further extended the use of WCA to locate ultimate flowrate targets for water network with regeneration placement. Besides, Ng et al. (2007) also presented insight-based targeting techniques to synthesise an optimal total network which consists of water reuse/recycle, regeneration, and wastewater treatment. In 2009, Ng et al. (2009) presented automated targeting approach which provides flexibility in changing the objective function to locate water targets and operating cost. A design method for flexible water networks with regeneration processes was introduced recently by Poplewski (2014) to determine minimum operating and investment costs. Note that in the abovementioned works, water and materials are recovered based on their quality. However, there is a limitation for recovery, in case the water streams have the same quality. In the previous approaches, the water/material with same quality can be recovered without priority.

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In this work, material flow cost accounting (MFCA)–based approach which incorporated the concept of prioritisation is proposed to solve this limitation in synthesising and optimising of total water network. This approach able to determine the hidden cost of each waste streams, which is overlooked in conventional accounting approach. In addition, an optimum total water network with minimum total operating cost can be targeted based on hidden cost as well as water quality. A conceptual case study, integrated sago starch extraction plant with wastewater treatment plant, is solved to illustrate the proposed approach.

## 2. Problem Statement

The problem definition for synthesis and optimisation of total water network is stated as follows: A set of process source, $h \in H$ generate a fixed flowrate, $F_h$ of wastewater with fixed concentration of contaminant $b$, $CC_{h,b}$. The wastewater is either sent to treatment unit $t$ with flowrate, $F_{h,t}^{WW}$ or reused/recycled to a set of process sinks $j \in J$ with flowrate of $F_{h,j}^{REC}$, as shown in Figure 1. Each treatment unit $t \in T$ is given total inlet flowrate of $F_t^{IN}$, and removal efficiency of $\eta_{t,b}$. Note that part of the treated water from treatment unit $t$ can also be reused/recycled into the process sink $j$ with flowrate of $F_{t,j}^{REC}$. Such water is known as regenerated water. The remaining treated water will be further treated in next treatment unit $t$ to meet discharge limit ($CC_b^{LIMIT}$). The total discharged flowrate is denoted as $F^{DIS}$. For each process sinks $j$, total inlet flowrate and concentration limit are given as $F_j^{IN}$ and $CC_{j,b}^{LIMIT}$. In order to incorporate the concept of prioritisation in synthesising an optimum total water network, hidden cost of each discharged stream is determined by quantifying the discharged waste in monetary units using the proposed approach.

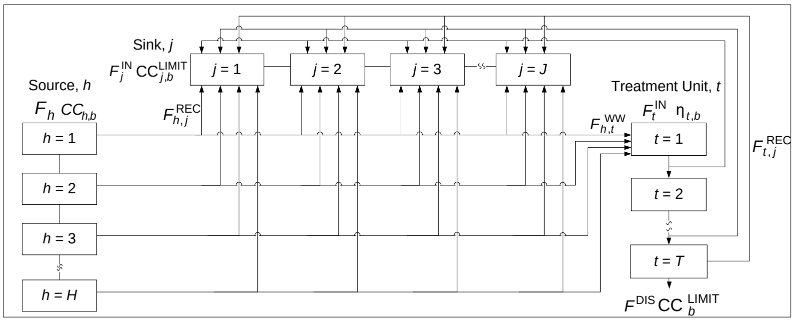


*Figure 1: Superstructure of total water network*

## 3. Formulation for MFCA-based Approach

### 3.1 Mass Balances

Flowrate balances of process source $h$, $F_h$ and treatment unit $t$, $F_t^{IN}$ are given as Eq(1) – (3):

$$F_h = \sum_{t=1}^{T} F_{h,t}^{WW} + \sum_{j=1}^{J} F_{h,j}^{REC} \qquad \forall h \qquad (1)$$

$$F_t^{IN} = \sum_{h=1}^{H} F_{h,t}^{WW} \qquad \forall t \qquad (2)$$

where $F_{h,t}^{WW}$ is the flowrate of wastewater that sent from process source $h$ to treatment unit $t$, while $F_{h,j}^{REC}$ is the recycled flowrate from process source $h$ to process sink $j$ Assuming there is no water loss in the treatment unit, the inlet flowrate of the treatment unit is equal to the output of the system. Note that the output of the system can be divided into reuse/recycle flowrate to process sink $j$ ($F_{t,j}^{REC}$) and treatment flowrate to next treatment unit $t$ ($F_{t+1}^{IN}$) as well as flowrate of sludge ($F_t^{SLUD}$) as show as below:

$$F_t^{IN} = \sum_{j=1}^{J} F_{t,j}^{REC} + F_{t+1}^{IN} + F_t^{SLUD} \qquad \forall t \qquad (3)$$

In the last treatment unit, $t$ = $T$, the flowrate of $F_{t+1}^{IN}$ is equal to total flowrate of water discharged to environment ($F^{DIS}$) given as:

$$F_{T+1}^{\mathrm{IN}} = F^{\mathrm{DIS}} \tag{4}$$

For each process sink $j$, $F_j^{\mathrm{IN}}$ can be determined by summation of flowrate from process source $h$ ($F_{h,j}^{\mathrm{REC}}$) and treatment unit $t$ ($F_{t,j}^{\mathrm{REC}}$). In addition, $F_j^{\mathrm{IN}}$ is required to meet inlet flowrate requirement ($F_j^{\mathrm{REQ}}$) given as:

$$F_j^{\mathrm{REQ}} = \sum_{t=1}^{T} F_{t,j}^{\mathrm{REC}} + \sum_{h=1}^{H} F_{h,j}^{\mathrm{REC}} \qquad \forall j \tag{5}$$

**3.2 Contaminant Balances**

The wastewater of each process source $h$ is characterised with a fixed concentration of contaminant $b$, $CC_{h,b}$ and sent to first treatment unit $t$ with a fixed contaminant removal efficiency of $\eta_{t,b}$. After the treatment in first unit $t$, the concentration of treated water ($CC_{t,b}^{\mathrm{OUT}}$) can be determined via a generic equation as Eq(6):

$$CC_{t,b}^{\mathrm{OUT}} = \frac{\left(\sum_{h=1}^{H} CC_{h,b} F_{h,t}^{\mathrm{WW}}\right)(1-\eta_{t,b})}{F_t^{\mathrm{WW\_OUT}}} \qquad \forall t \forall b \tag{6}$$

where $F_t^{\mathrm{WW\_OUT}}$ is total flowrate of treated water of treatment unit $t$. This treated water with concentration of $CC_{t,b}^{\mathrm{OUT}}$ is then either reused/recycled to process sinks $j$ with flowrate $F_{t,j}^{\mathrm{REC}}$ or further treated in next treatment unit $t$ ($t$+1) with flowrate $F_{t+1}^{\mathrm{IN}}$. Note that, in last treatment unit ($t$=$T$), the discharge concentration with contaminant $b$ to environment has to be lower than the discharged limit ($CC_b^{\mathrm{LIMIT}}$), as shown below:

$$CC_b^{\mathrm{LIMIT}} \geq \frac{\left(CC_{T-1,b}^{\mathrm{OUT}} F_T^{\mathrm{IN}}\right)(1-\eta_{T,b})}{F^{\mathrm{DIS}}} \qquad \forall b \tag{7}$$

where $CC_{T-1,b}^{\mathrm{OUT}}$ is the concentration of the treated water that sent from previous treatment unit (*T-1)* to treatment unit $T$ with flowrate of $F_T^{\mathrm{IN}}$. Besides, the wastewater from process source $h$ with concentration $CC_{h,b}$ can also be direct recycled to process sink $j$ without any treatment. This direct recycled wastewater is mixed with the reused/recycled treated water from treatment unit $t$ to process sink $j$. The combined concentration of these inlet water to process sinks $j$, $CC_{j,b}^{\mathrm{IN}}$ should be lower than the maximum limit of each process sink $j$ ($CC_{j,b}^{\mathrm{LIMIT}}$) as given below:

$$CC_{j,b}^{\mathrm{LIMIT}} \geq \frac{\sum_{h=1}^{H} CC_{h,b} F_{h,j}^{\mathrm{REC}} + \sum_{t=1}^{T} CC_{t,b}^{\mathrm{OUT}} F_{t,j}^{\mathrm{REC}}}{F_j^{\mathrm{IN}}} \qquad \forall j \forall b \tag{8}$$

**3.3 Cost Analysis**

To simplify the model, any process or unit from process source $h$, sink $j$ and treatment unit $t$ are represented by process $i$. Meanwhile, process $i'$ is represented the upstream or downstream processes of process $i$. In order to determine hidden cost (HC) of process $i$, $COST_i^{\mathrm{HC}}$, process cost, $COST_i^{\mathrm{PC}}$ and carried-forward cost, $COST_i^{\mathrm{CFC}}$ are taken into consideration as given below:

$$COST_i^{\mathrm{HC}} = COST_i^{\mathrm{PC}} + COST_i^{\mathrm{CFC}} \qquad \forall i \tag{9}$$

Process cost, $COST_i^{\mathrm{PC}}$ can be determined via summation of material cost, $COST_i^{\mathrm{MAT}}$, energy cost, $COST_i^{\mathrm{ENGY}}$, and system cost, $COST_i^{\mathrm{SYM}}$, as given below:

$$COST_i^{\mathrm{PC}} = COST_i^{\mathrm{MAT}} + COST_i^{\mathrm{ENGY}} + COST_i^{\mathrm{SYM}} \qquad \forall i \tag{10}$$

Meanwhile, carried-forward cost, $COST_i^{\mathrm{CFC}}$ , the cost carried from upstream or downstream process of the process *i*, can be determined via:

$$COST_i^{\mathrm{CFC}} = \sum_{i'=1}^{I'}\sum_{k=1}^{K} COST_{i',i,k} + \sum_{i'=1}^{I'} COST_{i',i}^{\mathrm{REC}} \qquad \forall i \tag{11}$$

where $COST_{i',i,k}$ is the cost carried by intermediate material *k* with flowrate $F_{i',i,k}$ and $COST_{i',i}^{\mathrm{REC}}$ is the cost carried by reused/ recycled water with flowrate $F_{i',i}^{\mathrm{REC}}$ from process *i'* to process *i*. For example, in case the intermediate material *k* of process source *h* is the wastewater (WW) that transferred from process source *h* to treatment unit *t* for treatment, $F_{i',i,k}$ can be re-wrote as $F_{h,t}^{\mathrm{WW}}$. Besides, $F_{i',i}^{\mathrm{REC}}$ can be re-wrote as $F_{h,j}^{\mathrm{REC}}$ and $F_{t,j}^{\mathrm{REC}}$ for the case the water is reused/recycled to process sink *j* from process source *h* or treatment unit *t*. To determine $COST_{i',i,k}$ and $COST_{i',i}^{\mathrm{REC}}$ , Eq(12) and Eq(13) are included in the model:

$$COST_{i',i,k} = \sum_{i'=1}^{I'} \frac{F_{i',i,k}}{F_{i'}^{\mathrm{out}}} COST_{i'}^{\mathrm{HC}} \qquad \forall i \tag{12}$$

$$COST_{i',i}^{\mathrm{REC}} = \sum_{i'=1}^{I'} \frac{F_{i',i}^{\mathrm{REC}}}{F_{i'}^{\mathrm{out}}} COST_{i'}^{\mathrm{HC}} \qquad \forall i \tag{13}$$

where $F_{i'}^{\mathrm{out}}$ is total output flowrate of process *i'* and $COST_{i'}^{\mathrm{HC}}$ is HC of process *i'*. Based on Eqs(9) – (13), HC of process *i* can be computed. To determine HC of discharged waste y from process *i*, $COST_{i,y}^{\mathrm{HC}}$ , total output flowrate of process *i*, $F_i^{\mathrm{out}}$, is first to be determined via :

$$F_i^{\mathrm{out}} = F_{i,i',k} + F_{i,p} + F_{i,w} \qquad \forall i \tag{14}$$

where $F_{i,i',k}$ and $F_{i,p}$ represent the flowrate of intermediate materials *k* and products *p*. Meanwhile, $F_{i,w}$ is given as flowrate of wastes *w* which can either be reused/recycled to other process *i'*, $F_{i,i'}^{\mathrm{REC}}$ or discharged wastes, $F_{i,y}$. Note that index *y* represents different types of discharged wastes (e.g., discharged water and disposed sludge). For discharged water, $F_{i,y}$ can be re-wrote as $F^{\mathrm{DIS}}$ when *t*=*T*. Besides, $F_{i,y}$ also can be used to represent $F_t^{\mathrm{SLUD}}$, disposed sludge from treatment *t*. To determine $COST_{i,y}^{\mathrm{HC}}$ , $F_{i,y}$ is divided by $F_i^{\mathrm{out}}$ to determine hidden unit cost (HUC) of discharge waste, $F_{i,y}^{\mathrm{HUC}}$ and then multiplied with $COST_i^{\mathrm{HC}}$ as below:

$$COST_{i,y}^{\mathrm{HC}} = \sum_{i'=1}^{I'} \frac{F_{i,y}}{F_i^{\mathrm{out}}} COST_i^{\mathrm{HC}} \qquad \forall i \tag{15}$$

To determine total HC of discharged waste, $TotCOST^{\mathrm{HC}}$ , all $COST_{i,y}^{\mathrm{HC}}$ from process *i* are summed up as given as below:

$$TotCOST^{\mathrm{HC}} = \sum_{i=1}^{I}\sum_{y=1}^{Y} COST_{i,y}^{\mathrm{HC}} \tag{16}$$

The total operation cost (TOC) can be determined via:

$$TOC = TotCOST^{\mathrm{HC}} + TotCOST^{\mathrm{DIS}} + TotCOST^{\mathrm{PC}} \tag{17}$$

where $TotCOST^{DIS}$ is total disposal cost and $TotCOST^{PC}$ is total processing cost. In order to target an optimal total water network with minimum TOC, an optimisation objective is set as Eq(18).

Minimise $TOC$ (18)

Note that this model is a non-linear program which can be solved via commercial optimisation software, LINGO, version 13 with global solver that uses a branch-and-bound algorithm to find optimal solutions (Gau and Schrage, 2003). A conceptual case study, integrated sago starch processing plant with wastewater treatment plant is solved to illustrate the proposed approach.

## 4. Case Study

Sago starch can be extracted from sago logs via several processes (see Figure 2). As shown, large amount of water is required during the processes of rasping (RPG), fiber separation (FSEP) and sieving (SIEV). The water is either sourced from river via water treatment plant (WTP) and/or freshwater from local authorities. In this case study, a total flowrate of 66 $m^3$/d, 132 $m^3$/d, and 144 $m^3$/d of water inlet is required for RPG, FSEP and SIEV (see Figure 2). Meanwhile, sago wastes (wastewater and fibre) are generated from FSEP, SIEV, SWSEP and FILT processes. The wastewater dashed line in Figure 2 can be either reused/recycled to existing processes (WTP, RPG, FSEP, and SIEV) or sent to wastewater treatment plant. In this case study, the treatment plant composed of chemical, biological, tertiary and sludge treatment processes. The wastewater is being treated in sequence of treatment unit to reduce impurities loads. The treated water from waste treatment system can be reused/recycled to the processes or further treated in next treatment process.

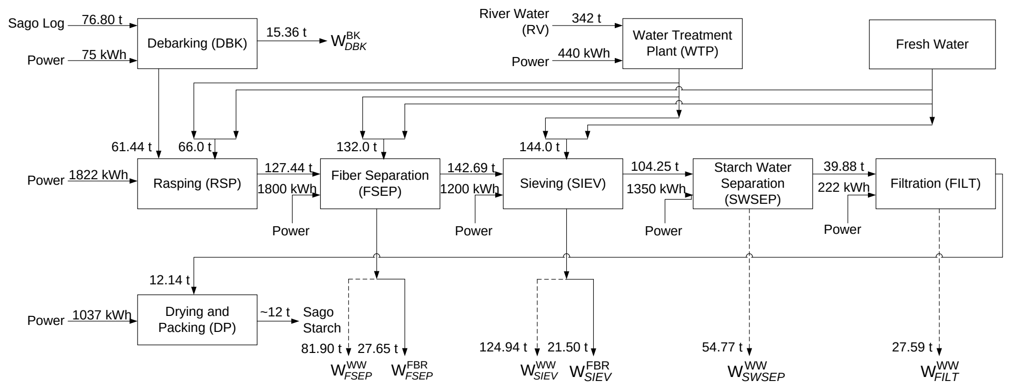


*Figure 2: Process block diagram for sago starch processing*

Based on Eqs(1) – (18), the case study is solved and an optimal solution is found as showed in Figure 3. As shown, the wastewater (0.38 $m^3$/d and 0.96 $m^3$/d) from process FSEP which possessing lowest HUC (5.04 USD/$m^3$) is reused/recycled. Meanwhile, process FILT which generated only wastewater also

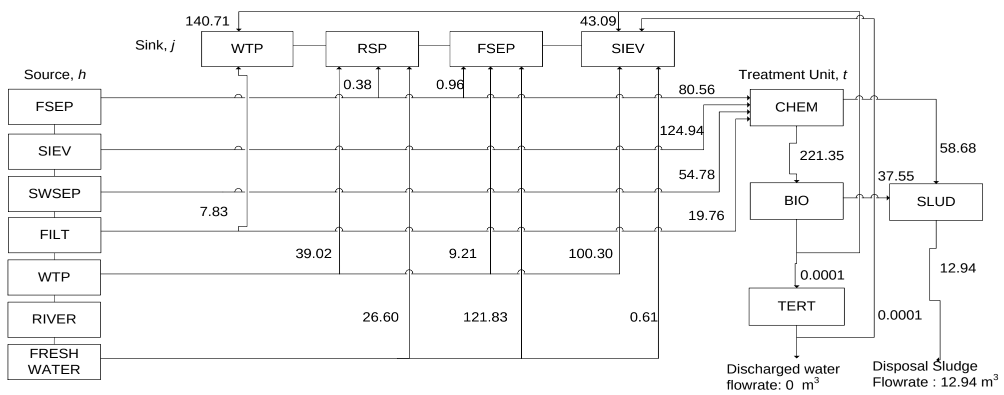


*Figure 3: Results for total water network of sago starch processing*

reused/recycled 7.83 $m^3$/d of wastewater as it possessing highest HUC (12.87 USD/$m^3$). The remaining wastewater from FSEP (80.56 $m^3$/d), SIEV (124.94 $m^3$/d), SWSEP (54.78 $m^3$/d) and FILT (19.76 $m^3$/d) is then sent to chemical treatment process. Total 58.68 $m^3$/d of sludge is generated in chemical process, while all the treated water (221.35 $m^3$/d) is sent to biological process for further treatment. Since the treated water from biological treatment is characterised with lower concentration than chemical treatment, and possessing higher HUC (10.00 USD/$m^3$) than chemical treatment (9.52 USD/$m^3$). Hence, treated water from biological treatment process is prioritised to reuse/recycle (140.71 $m^3$/d and 43.09 $m^3$/d) to WTP and SIEV before to next treatment unit. Meanwhile, 37.55 $m^3$/d of sludge is generated and negligible amount of treated water (0.0001 $m^3$/d) is sent to tertiary treatment process. All this treated water (0.0001 $m^3$/d) is then fully reused in SIEV. Hence, no water is discharged to environment. Besides, in order to fulfil the inlet water requirement of RPG, FSEP and SIEV, 39.02 $m^3$/d, 9.21 $m^3$/d, and 100.30 $m^3$/d of water from WTP and 26.60 $m^3$/d, 121.83 $m^3$/d, and 0.61 $m^3$/d of fresh water are sent to RPG, FSEP and SIEV as shown in Figure 3. On the other hand, it is noted that total 183.80 $m^3$ of freshwater or river water are saved by wastewater recovery in this targeted optimum total water network.

## 5. Conclusions

MFCA-based approach which incorporated the concept of prioritisation for waste recovery is proposed for synthesis and optimisation of total water network. Based on the proposed approach, an optimal total water network which consists of multiple fixed removal efficiency treatment units can be synthesised. In addition, minimum total operating cost of a total water network, which considered multiple contaminants in water, can be targeted.

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