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Material Flow Cost Account-based Approach for Synthesis and Optimisation of Wastewater Treatment Plant

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Sago industry is an important industry in East Malaysia (mainly Sarawak). Sago starch is produced as an alternative carbohydrate source in the food chain. To produce one tonne of sago starch, a minimum of 20 tonnes of sago wastewater would be generated. In order to comply with local regulation and to reduce environmental impacts, the produced wastewater requires proper wastewater treatment (WWT). However, with several WWT technologies available in the market, this becomes a challenge for decision makers to select WWT technologies with minimum investment cost while meeting discharge regulations. As shown in the previous research works, the investment cost can be minimised by reducing the resources used. This can be done by reused and recycled the treated water within the processes. Apart from this, the cost for waste (sludge cake) generation should be minimised since the sludge cake will not bring any value to the WWT plant. This can be addressed by using the concept of Material Flow Cost Accounting (MFCA). MFCA is a management tool which quantifies material flows across a production process in both physical and monetary values. The application of MFCA had been adapted in previous research works to prioritise waste streams for waste recovery and to reduce investment costs for WWT plants. In this work, MFCA is further extended to a more comprehensive and realistic WWT plant optimisation, taking into account of sludge treatment. The proposed MFCA can determine the monetary value associated with sludge cake production within the WWT plant. To illustrate the proposed approach, a sago-based WWT plant is solved in this work.

1. Introduction

Material Flow Cost Accounting (MFCA) was first developed in year 2005 as a tool in Environmental Management Accounting by International Federation of Accountants (2005). At its early stages, MFCA was established to measure the material flow in production lines in terms of physical and monetary values for management decision making (Kokubu, 2015). The concept of MFCA was then used in assessing monetary values within the manufacturing streams for cost minimisation (Wang, 2015). According to Kokubu (2015), the investment cost that was put into a manufacturing process would not only be used for production of desired product but also for generation of by-product (or waste). Apart from this, the waste requires additional cost for treatment before discharged to the environment. Therefore, the cost that associated to waste streams (waste generation cost) must always be minimised to reduce the loss of profit. Since MFCA can be used to track monetary values in every stream in a process, it was adapted for waste recovery prioritisation (Wan et al., 2015). Most conventional accounting practices in manufacturing process consider operating cost (OC) such as material cost, labor cost and system cost. However, Wan et al. (2015) had proposed two novel parameters to track the cost incurred at every stream of process. These two novel parameters are known as hidden cost (HC) and carry forward cost (CFC). HCs are the incurred cost that was embedded in each stream. Meanwhile, CFC is referred to the HC that is carried forward and incurred in the next stage of process. Therefore, HC in waste streams should be minimised. Later, Siew et al. (2018) adapted the proposed approach for selection of WWT technologies with minimum total cost of wastewater treatment. However, sludge treatment system was not taken into consideration in the previous work (Siew et al., 2018). As such, in this work, a more extended

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and complete MFCA model is proposed with consideration of sludge treatment system. In a WWT plant, treated wastewater and sludge cake are two common final products. The treated wastewater could be reused/recycled within the manufacturing process to minimise the consumption of fresh water sources and to increase economic performance of the process. Subsequently, the HC incurred in the sludge cake stream is considered as waste generation cost. This is because the sludge cake cannot be recovered to the process and it requires additional disposal cost. Hence, the optimisation objective in this work is to miminise the waste generation cost. In addition, the removal relationship between contaminants (i.e., TSS, COD and BOD) is included in the model to avoid oversizing of treatment stages. For example, if 1 kg of TSS is removed, it will indirectly remove a certain amount of COD and BOD. In order to illustrate the proposed approach, an industrial case study is solved and discussed in this work.

2. Problem statement

The problem definition for the extended MFCA model is as follows: An inlet wastewater feed would be transferred and treated with a series of wastewater treatment; which includes, preliminary treatment $a \in A$, chemical treatment $b \in B$, biological treatment $c \in C$, tertiary treatment $d \in D$ and sludge treatment $e \in E$, as shown in Figure 1. As both chemical and biological treatment would generate certain amount of sludge, a portion of the flowrate will diverge further into sludge treatment process. Based on Figure 1, a mathematical model was formulated in Section 3.

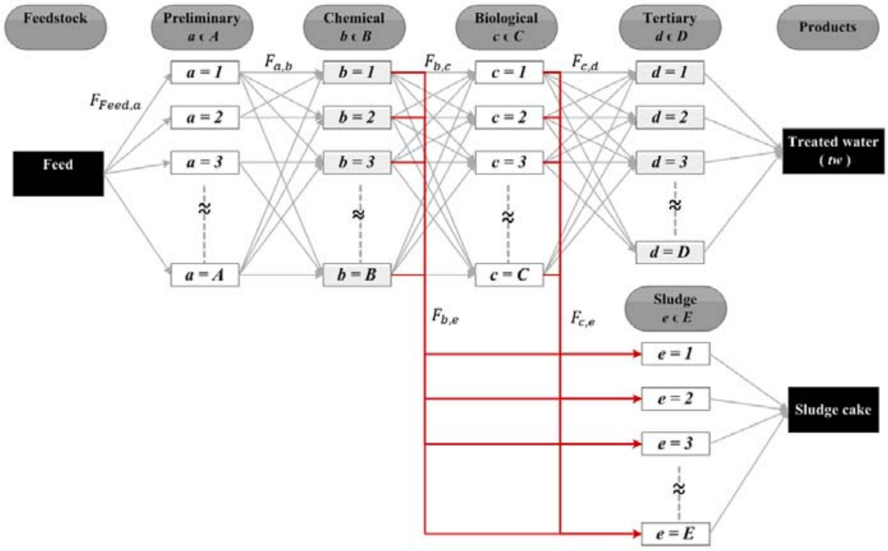

Figure 1: Generic superstructure of conventional wastewater treatment process

3. Material Flow Cost Accounting (MFCA) based optimisation

Figure 1 indicates that the flowrate balance, contaminant balance and cost computation equations would repeat in each treatment stage. In this respect, a more generic set of equations (Eqs.(1) to (9)) is formulated. The generic formulation assigns index i to represent preceding treatment stage, index j to represent current treatment stage, and index k to represent succeeding treatment stage respectively. For example, to formulate the equations for chemical stage b, the current index j will be chemical stage b (j = b), the previous index i will be preliminary treatment stage a (i = a) and subsequent index k will be biological treatment stage c (k = c). The same formulation method is repeated for other stages. The following sub-sections describe the generic formulation for flowrates, contaminants and costs.

3.1 Flowrate balance

The generic equations of volumetric flowrate balance are shown in Eqs(1) – (3). As shown, F_j^{in} (m^3/day) and F_j^{out} (m^3/day) are the inlet and outlet flowrate of current treatment stage j, respectively. Meanwhile, $F_{i,j}$ (m^3/day) is the flowrate transferred from preceding treatment stage i to current treatment stage j and $F_{j,k}$ (m^3/day) is the flowrate transferred from current treatment stage j to succeeding treatment stage k.

$$F_j^{in} = \sum_{i=1}^{I} F_{i,j} \qquad \forall j \qquad (1)$$

$$F_j^{in} = F_j^{out} \qquad \forall j \qquad (2)$$

$$F_j^{out} = \sum_{k=1}^{K} F_{j,k} \qquad \forall j \qquad (3)$$

3.2 Contaminant balance

The generic contaminant balance equations for contaminant *n* on current treatment stage *j* were formulated as shown in Eqs(4) to (6) where the contaminant *n* can be COD, BOD, TSS and other contaminants. The X_j in Eq 5 refers to the contaminant removal efficiency (kg contaminant/m^3 WWT) each technology *j*. As shown, $M_{j,n}^{in}$ (kg/day) and $M_{j,n}^{removed}$ (kg/day) are the mass of contaminant *n* entering and removed from technology *j* respectively. In addition, $C_{j,n}^{in}$ (kg/m^3) is the concentration of *contaminant n* in the inlet stream of technology *j.*

$$M_{j,n}^{in} = C_{j,n}^{in} F_j^{in} \qquad \forall j \forall n \qquad (4)$$

$$M_{j,n}^{removed} = M_{j,n}^{in} \, x_{j,n} \qquad \forall j \forall n \qquad (5)$$

$$M_{j,n}^{in} = M_{j,n}^{removed} + \sum_{k=1}^{K} M_{j,k,n} \qquad \forall j \forall n \qquad (6)$$

3.3 Cost computation

As mentioned previously, MFCA tracks the monetary value associated to each stream. Based on this concept, the cost of wastewater and sludge cake after being processed at succeeding treatment stages can be evaluated. The formulation of cost calculation in this work is based on total unit cost per flowrate of wastewater. The unit operating cost for each technology *j*, $UCost_j^{opt}$ (USD/m^3) are attributed to the unit material cost, UCost_j^{mat} and unit power cost, UCost_j^{power} . Meanwhile, the actual operating cost for technology *j*, $Cost_j^{opt}$ (USD/day) required can be determined by multiplying the unit operating cost for technology *j*, $UCost_j^{opt}$ with flowrate entering the technology j, F_j^{in} . Similarly, the operating cost generated will be associated to the outlet flowrates and will be brought forward from current technology *j* to succeeding technology *k* as carried forward cost, $CFC_{j,k}$ (USD/day). A series of generic cost computation equations on treatment stage *j* are formulated as shown in Eqs.(7) to (9).

$$UCost_j^{opt} = \mathrm{UCost}_j^{mat} + \mathrm{UCost}_j^{power} \qquad \forall j \qquad (7)$$

$$Cost_j^{opt} = UCost_j^{opt} F_j^{in} \qquad \forall j \qquad (8)$$

$$CFC_{j,k} = UCost_j^{opt} F_{j,k} \qquad \forall j \forall k \qquad (9)$$

Lastly, the cost accrued in sludge cake stream exiting sludge treatment *e* is considered as hidden cost since it is the final product and will not be further carried forward. Therefore, to trace the hidden cost of sludge cake produced, equation (9) is applied to the sludge cake product stream in sludge treatment *e* by replacing CFC as HC. As shown in Eq (10), the hidden cost of sludge cake, $HC_e^{sludgecake}$ (USD/day) generated can be determined by multiplying the unit operating cost of sludge treatment *e*, $UCost_e^{opt}$ and the flowrate of sludge cake exiting sludge treatment *e*, F_e^{out} . The total hidden cost of sludge cake, $HC_e^{sludgecake}$ generated at sludge treatment *e* is equated to the total waste generation cost for sludge cake, $WGC^{sludgecake,total}$ as shown in Eq (11). Following this, the optimisation objective is to minimise the total waste generation cost as shown in Eq (12).

$$HC_e^{sludgecake} = UCost_e^{opt} F_e^{out} \qquad \forall e \qquad (10)$$

$$WGC^{sludgecake,total} = \sum_{e=1}^{E} HC_e^{sludgecake} \tag{11}$$

$$Min = WGC^{sludgecake,total} \tag{12}$$

4. Case study

In this case study, organic WWT plant for water reuse/recycle in a sago-based biorefinery in Sarawak is presented. Figure 2 illustrates the superstructure of an organic WWT plant consisting different technologies at different treatment stages. Based on the technologies considered for the case study, fixed input parameters were gathered. It is required to ensure treated water would comply with standard discharged regulation Standard A (Department of Environment, 2013) as shown in Table 1 and inlet wastewater characteristics obtained from a sago mill company in Sarawak (Wan et al., 2016). The flowrate of the wastewater discharge from process to WWT is recorded as 276 m^3/day. The contaminant removal efficiency of each technology provided by industrial partners is summarised in Table 2. Table 3 shows the dryness efficiency of each sludge treatment technology. Lastly, Table 4 shows the operating cost which includes the chemical cost and power cost for each listed technology at each treatment stage. According to Tenaga Nasional Berhad (TNB) (2018), the electricity rates (assuming full capacity usage) for Heavy Industry class E1 is USD 7.24/kW effective from January 2018 until year 2020.

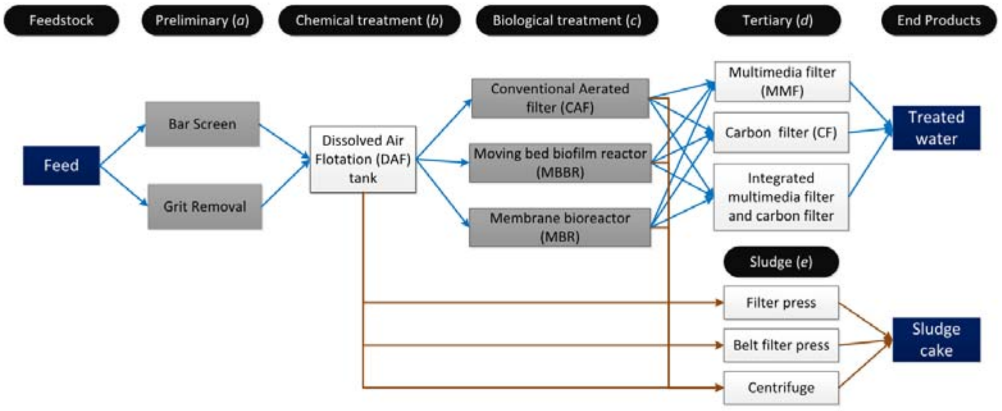

Figure 2: Case study superstructure for organic wastewater treatment.

Table 1: Sago wastewater contaminants characteristic (Wan et al, 2015) and discharged regulations by Department of Environment (2013).

Concentration (ppm)	TSS	COD	BOD
Sago wastewater	4,942	7,763	3,362
Discharge regulations (Standard A)	50	80	20

Table 2: Contaminant removal efficiency of wastewater treatment technologies

		Removal efficiency (%)		
	Technologies	TSS	COD	BOD
Preliminary treatment	Bar Screen	65	0	0
	Grit Removal	40	0	0
Chemical treatment	Dissolved air flotation (DAF)	91	70	65
Biological treatment	Conventional aerated filter (CAF)	85	85	87
	Moving bed biofilm reactor (MBBR)	85	90	92
	Membrane bioreactor (MBR)	99	90	90
Tertiary treatment	Multimedia filter (MMF)	90	0	0
	Carbon filter (CF)	0	85	85
	Integrated multimedia filter and carbon filter (MMF + CF)	90	85	85

Table 3: Dryness of sludge cake produced by each sludge treatment technology (Faure Equipments, 2018).

Technologies	Dryness (kg SS/m^3)
Filter press	25
Belt filter press	29.9
Centrifuge press	28.5

Table 4: Operating cost of WWT technologies by Gu et al. (2017).

	Technologies	Unit Cost (USD/m^3)		
		Chemical cost	Power cost	Opt. cost
Preliminary treatment	Bar Screen	0	0	0
	Grit Removal	0	0	0
Chemical treatment	Dissolved air flotation (DAF)	0.13	0.05	0.18
Biological treatment	Conventional aerated filter (CAF)	0.04	0.64	0.67
	Moving bed biofilm reactor (MBBR)	0.04	0.48	0.52
	Membrane bioreactor (MBR)	0.04	0.86	0.89
Tertiary treatment	Multimedia filter (MMF)	0	0.02	0.02
	Carbon filter (CF)	***	0.02	0.02
	Integrated multimedia filter and carbon filter (MMF + CF)	0	0.04	0.04
Sludge treatment	Filter press	0.12	0.60	0.72
	Belt filter press	0.12	0.36	0.48
	Centrifuge press	0.12	0.48	0.60

**** 1kg carbon needed for every 0.2 kg COD removed; where, carbon price = USD 2.00/kg*

Based on the input parameters in Tables 1 – 4, the case study is solved with a commercial optimisation software, LINGO version 18, in a computer with specification of Intel ® Core ™ i7-6500U @ 8 GB RAM, x64-based processor. Based on the global optimum results, the wastewater treatment pathways with minimum waste generation cost (WGC) are bar screen, dissolved air floatation (DAF), conventional aerated filter (CAF), carbon filter (CF) and belt filter press as shown in Figure 3. The concentration of contaminants in the treated water are reported as 37 ppm of COD, 6 ppm of BOD and 26 ppm of TSS which complied with Standard A as shown in Table 1. Based on the flowrate distribution in Figure 3, the hidden cost (USD/day) which are associated to each stream can be computed based on the operating unit cost as shown in Figure 4. As illustrated, the hidden cost which are embedded in each stream are consecutively accumulated and carried forward to the next stage. For every USD 76.25/day spent on the wastewater treatment process, USD 1.96/day value of sludge cake will be disposed which is approximately 2.6% from the investment. Meanwhile, the remaining 97.4% of the investment will be utilised back into the sago biorefinery process.

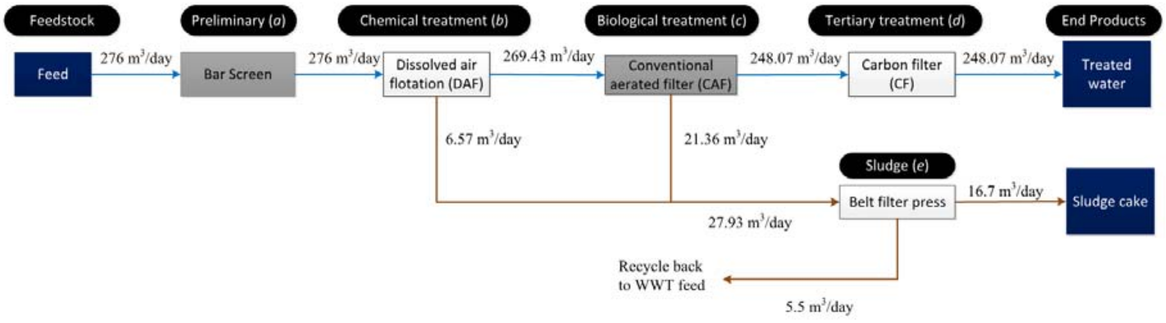

Figure 3: Flowrate distribution for optimum pathway with minimum WGC.

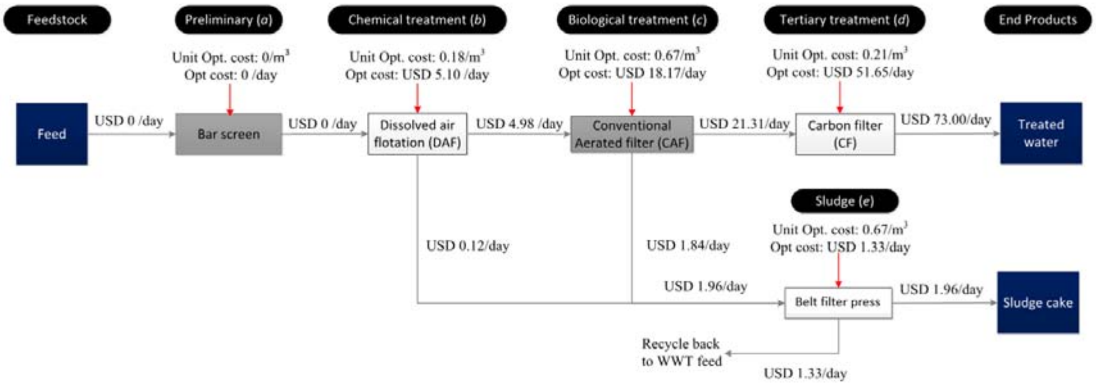

Figure 4: Cost distribution for optimum pathway with min. WGC.

5. Conclusions

Wastewater treatment is a complementary process in every manufacturing plant. WWT is considered as an extra disbursement which reduces the profit gain of the company. Due to this reason, many cases of direct discharge of untreated wastewater occur in our society today. This prominently increases water pollution as well as disrupting the water cycle. Therefore, this research work had adapted the concept of Material flow cost accounting (MFCA) as an approach to develop a mathematical modelling optimisation tool. This developed approach serves as a guideline and decision-making tool for engineers to synthesise a cost-effective wastewater treatment pathway to maximise the profit gain of company. The developed approach was then shown using a sago wastewater case study. Results from the case study indicate that the optimised wastewater treatment pathway with minimum waste generation cost, was capable to recover as much as 97.4% of the capital investment back into the process. As future work, capital cost can be included to make the model more realistic and accurate. In addition, carbon footprint can also be included as an additional objective into the model to further enhance the WWT process optimization.

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