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Synthesis of Resource Conservation Network for the Clay Bath System in Palm Oil Mills

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This work presents a mathematical model for resource conservation in a palm oil milling process via property integration. The focus is given to the clay bath system for solid separation based on density differences. In the present study, the clay bath is modeled as a semi-batch unit with dynamic changes. This is different from previous works where the clay bath is treated as a continuous unit with constant feed and effluent flow rates. The design problem is formulated as a nonlinear program based on a superstructure, with the objective function to minimize fresh resource consumption.

1. Introduction

Process integration is defined as *a holistic approach to process design and operation that emphasizes the unity of the process* (El-Halwagi, 1997, 2006). The main idea of process integration is to explore opportunities for energy and mass recovery via heat exchange and material reuse/recycle. This approach serves as a more aggressive strategy for pollution prevention than conventional end-of-pipe waste treatment activities (for pollution control), in responding to the increase of public awareness of environmental sustainability, rising cost of raw materials, and ever-tightening emission legislation.

Over the past few decades, numerous works have been reported for process plants to reduce fresh resource consumption and waste generation, or to minimize total costs by synthesizing resource conservation networks (RCNs). In particular, the most common case of RCN is water network synthesis (Bagajewicz, 2000; Foo, 2009; Jeżowski, 2010) where the proposed methodologies can be broadly categorized as pinch analysis and mathematical optimization. Note that most of the previous works are limited to chemo-centric or concentration-based systems where the quality of streams is measured in contaminant concentration. However, many design problems are based on stream properties such as density, pH, and viscosity. This led to the development of a new design paradigm of *property integration* (Shelley and El-Halwagi, 2000; El-Halwagi, 2006).

In this work, property integration is adopted to synthesize RCN in a palm oil milling process. The focus is given to the clay bath system that is used for kernel/shell

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separation. Previous works were reported by Ng et al. (2009) and Chen et al. (2010), where the clay bath was simplified as a continuous unit with constant input and output. However, in practice, the internal condition of the clay bath is disturbed by impurities of the kernel/shell mixture. Thus it is more practical to model the clay bath as a semi-batch unit with dynamic changes, and the material recovery strategy is adjusted accordingly to maintain its separation efficiency. This is the subject of the present study.

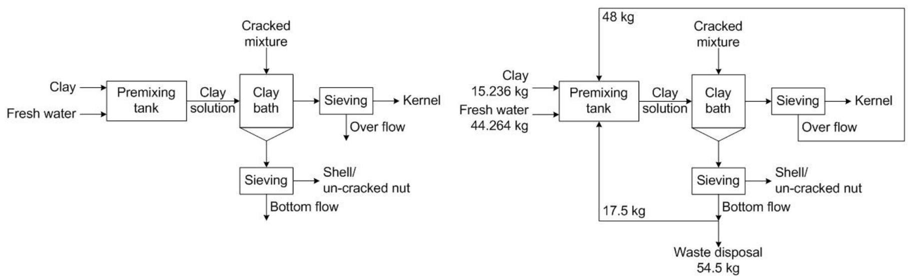
2. Problem Statement

The problem to be addressed in this work is property-based material recovery in a palm oil milling process. It can be briefly stated as follows:
The clay bath system has a set of process sources $i \in I$ and a set of process sinks $j \in J$. The sources may be considered for reuse/recycle to the sinks or sent for waste disposal. Besides, a set of fresh resources $r \in R$ are available for service. The objective is to determine the optimum operating condition that achieves the minimum fresh resource consumption, while satisfying all process constraints.
When several streams are mixed, a linearized property mixing rule is needed to define all possible mixing patterns among the individual properties (El-Halwagi, 2006):

$$\bar{f}\psi(\bar{p}) = \sum_{\dagger} f_{\dagger}\psi(p_{\dagger}) \quad (1)$$

where $\psi(p_{\dagger})$ and $\psi(\bar{p})$ are linearly-additive operators on stream property $p_{\dagger}$ and mixture property $\bar{p}$ respectively, while $\bar{f}$ is the total flow rates of individual streams:

$$\bar{f} = \sum_{\dagger} f_{\dagger} \quad (2)$$



(a) (b)

Figure 1: (a) A clay bath system; (b) optimal configuration of the clay bath system

3. Model Formulation

Figure 1(a) shows a schematic diagram of a clay bath system to separate palm kernel from the shell and un-cracked nut (based on the flotation principle). The clay bath consists of clay-water slurry whose proportions are chosen to achieve the desired density. Since the quality of the slurry may degrade during use (through inadvertent separation of the clay particles from water), and the cracked mixture contains impurities that affect the solution property in the clay bath, make-up water and clay are fed into the system to compensate for perturbations and to maintain the separation efficiency.

Based on the superstructure approach proposed by Chen et al. (2010), the clay bath can be treated as a storage vessel, with its feed (clay solution) and effluents (over and bottom flows) being considered as process sink and sources respectively. Moreover, to capture the dynamic behavior of the clay bath, the operating period is divided into a set of time intervals $t \in T$. The model formulation is presented as follows:

Splitting of source *i* to sinks *j* and/or waste disposal systems *w* in time interval *t*

$$F_i = \sum_{j \in J} f_{ijt} + \sum_{w \in W} f_{iwt} \qquad \forall i \in I \ , t \in T \tag{3}$$

where F_i is the flow rate of source *i*, while f_{ijt} and f_{iwt} are the flow rates from source *i* to sink *j* and disposal system *w* respectively.

Mixing of the streams from sources *i* and/or resources *r* to sink *j* in time interval *t*

$$f_{jt} = \sum_{i \in I} f_{ijt} + \sum_{r \in R} f_{rjt} \qquad \forall j \in J \ , t \in T \tag{4}$$

where f_{jt} and f_{rjt} are the flow rates of sink *j* and resource *r* to sink *j* in time interval *t* respectively. The sink flow rate may have a lower ($F_j^{\min}$) and upper bounds ($F_j^{\max}$):

$$F_j^{\min} \le f_{jt} \le F_j^{\max} \qquad \forall j \in J \ , t \in T \tag{5}$$

Property mixing equation for the streams to sink *j* in time interval *t*

$$f_{jt} \psi_{jpt} = \sum_{i \in I} f_{ijt} \Psi_{ip} + \sum_{r \in R} f_{rjt} \Psi_{rp} \qquad \forall j \in J \ , p \in P \ , t \in T \tag{6}$$

where ψ_{jpt} is the operator on property *p* to sink *j* in time interval *t*, while Ψ_{ip} and Ψ_{rp} are the operators on property *p* of source *i* and resource *r* respectively.

Sink constraints on properties:

$$\Psi_{jp}^{\min} \le \psi_{jpt} \le \Psi_{jp}^{\max} \qquad \forall j \in J \ , p \in P \ , t \in T \tag{7}$$

Flow balance around the clay bath in time interval *t*

$$q_t = Q^0\Big|_{t=1} + q_{t-1}\Big|_{t>1} + \left(\sum_{j \in J} f_{jt} - \sum_{i \in I} F_i \right) \Delta_t \qquad \forall t \in T \tag{8}$$

where q_t is the amount of slurry in the clay bath at the end of time interval *t*, Q^0 is the initial amount of slurry in the clay bath, and Δ_t is the length of time interval *t*.

Lower and upper bounds for the amounts of slurry in the clay bath:

$$Q^{\min} \le q_t \le Q^{\max} \qquad \forall t \in T \tag{9}$$

Property mixing equation around the clay bath in time interval *t*

$$q_t\psi_{pt}^{\mathrm{bath}} = Q^0\Psi_p^{\mathrm{bath},0}\Big|_{t=1} + q_{t-1}\psi_{p,t-1}^{\mathrm{bath}}\Big|_{t>1} + \left(\sum_{j\in J} f_{jt}\psi_{jpt} + \Phi_p^{\mathrm{cm}} - \sum_{i\in I} F_i\Psi_{ip}\right)\Delta_t \qquad \forall p\in P\ ,t\in T \qquad (10)$$

where $\psi_{pt}^{\mathrm{bath}}$ is the operator on property p of the slurry in the clay bath at the end of time interval t, $\Psi_p^{\mathrm{bath},0}$ is the operator on the initial property of the slurry in the clay bath, and Φ_p^{cm} indicates the property change of property p caused by the cracked mixture.
Property constraints for the slurry in the clay bath:

$$\Psi_p^{\mathrm{bath,min}} \le \psi_{pt}^{\mathrm{bath}} \le \Psi_p^{\mathrm{bath,max}} \qquad \forall p\in P\ ,t\in T \qquad (11)$$

The objective function is the minimization of fresh resource consumption, i.e.

$$\min obj = \sum_{r\in R}\sum_{j\in J}\sum_{t\in T} f_{rjt}\Delta_t \qquad (12)$$

Note that the formulation is a nonlinear program (NLP).

4. Illustrative Case Study

Table 1 shows the stream data for the clay bath system in Figure 1(a). As mentioned earlier, the over and bottom flows are two process sources that may be reused/recycled to the process sink to minimize the consumption of fresh water and clay. To maintain high separation efficiency of the cracked mixture, the slurry density in the clay bath should be regulated within the range of 1110-1130 kg/m^3, and the total suspended solid (TSS) content of the slurry should not exceed 0.5 wt%. Therefore, density and TSS are identified as the critical properties for material recovery.
The mixing rules for density and TSS are given as follows (Shelley and El-Halwagi, 2000; Chen et al., 2010):

$$\bar{f}\frac{1}{\bar{\rho}} = \sum_{\dagger} f_{\dagger}\frac{1}{\rho_{\dagger}} \qquad (13)$$

$$\bar{f}\,\overline{TSS} = \sum_{\dagger} f_{\dagger}TSS_{\dagger} \qquad (14)$$

Table 1: Stream data for the case study

	Flow rate (kg/h)	Density (kg/m^3)	TSS (wt. %)
Over flow	4	1018	0.08
Bottom flow	6	1200	0.2
Fresh water	To be optimized	1000	0
Clay	To be optimized	2600	0

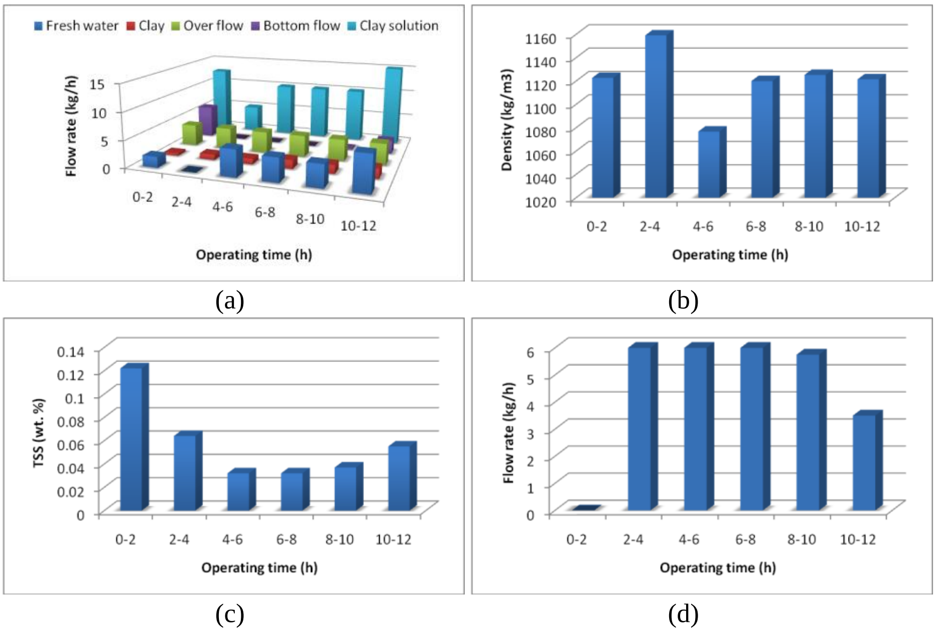
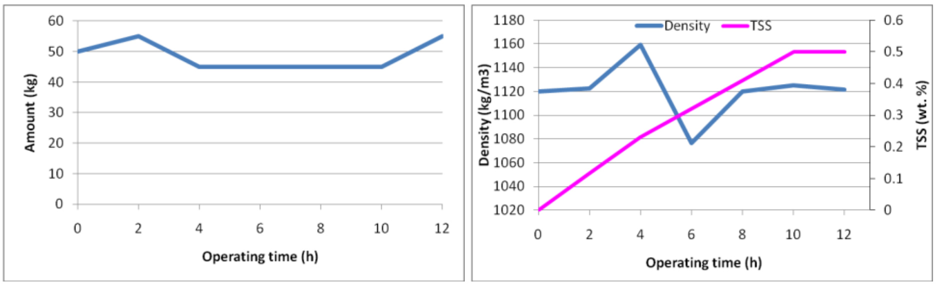


Figure 2: Feed condition of (a) flow rate, (b) density, and (c) TSS to the clay bath versus operating time; (d) flow rate of bottom flow disposal versus operating time

An initial condition of 50 kg, 1120 kg/m^3 density, and 0 wt. % TSS is assumed for the slurry in the clay bath. The amount of slurry should be kept within the range of 45-55 kg during the operation. Furthermore, the property changes (caused by the cracked mixture) to the slurry are estimated to be 0 m^3/h for density and 3.2 kg/h for TSS. In this case, the required period of a clay bath operation is 12 h, with an equal length of 2 h for each time interval. It is obvious that a shorter length of time intervals may lead to more accurate solution. However, this results in a larger number of time intervals that imply frequent manipulation, which is not practical for plant operation.

The NLP formulation that involves 121 constraints and 73 continuous variables was solved in 0.437 s, with BARON as the solver in GAMS environment on a Core 2, 2.53 GHz processor. The minimum consumptions of fresh water and clay are determined as 44.264 and 15.236 kg respectively over the 12 h period. Figure 1(b) shows the optimal configuration of the clay bath system. As shown, a total of 48 kg of the over flow and 17.5 kg of the bottom flow are recycled to prepare clay solution in 12 h, while a total of 54.5 kg of the bottom flow is sent for waste disposal. Figures 2(a)-(c) show the feed condition to the clay bath versus operating time, while Figure 2(d) shows the flow rate of bottom flow disposal versus operating time. In addition, Figure 3 shows the amount, density, and TSS of slurry in the clay bath versus operating time. Prior to the exploration of material reuse/recycle opportunities, the consumptions of fresh water and clay are 94.414 and 20.586 kg respectively, which can be obtained with the proposed model by omitting variable f_{ijt}. By comparison, the optimal result corresponds to 53.12% and 25.99% reductions for fresh water and clay respectively.



(a) (b)

Figure 3: Operating parameters of slurry content in the clay bath over time: (a) amount; (b) density and TSS

5. Concluding Remarks

A mathematical model for the synthesis of a property-based RCN in a clay bath system has been developed. The formulation is based on the superstructure proposed by Chen et al. (2010), where the dynamic behavior of the clay bath is addressed. This provides a more accurate process representation than those in the previous works.

References

Bagajewicz, M., 2000, A review of recent design procedures for water networks in refineries and process plants, Computers and Chemical Engineering 24, 2093−2113.

Chen, C.-L., Lee, J.-Y., Ng, D. K. S. and Foo, D. C. Y., 2010, A unified model of property integration for batch and continuous processes, AIChE Journal 56, 1845−1858.

El-Halwagi, M. M., 1997, Pollution Prevention through Process Integration: Systematic Design Tools. Academic Press, San Diego, USA

El-Halwagi, M. M., 2006, Process Integration. Elsevier, Amsterdam, the Netherlands

Foo, D. C. Y., 2009, State-of-the-art review of pinch analysis techniques for water network synthesis, Industrial and Engineering Chemistry Research 48, 5125−5159.

Jeżowski, J., 2010, Review of water network design methods with literature annotations, Industrial and Engineering Chemistry Research 49, 4475−4516.

Ng, D. K. S., Foo, D. C. Y., Tan, R. R., Pau, C. H. and Tan, Y. L., 2009, Automated targeting for conventional and bilateral property-based resource conservation network, Chemical Engineering Journal 149, 87−101.

Shelley, M. D. and El-Halwagi, M. M., 2000, Component-less design of recovery and allocation systems: a functionality-based clustering approach, Computers and Chemical Engineering 24, 2081−2091.