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Water-Wastewater Management of Tapioca Starch Manufacturing Using Optimization Technique

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ABSTRACT Water reuse is one promising method to reduce wastewater from several sources in chemical industry: Utilities and Processes. Moreover, water reuse can also recover valuable product leaving with waste streams. The objective of this work is to minimize the freshwater flowrate throughout the system and find out the optimum water network. A mass integration for segregation, mixing, reusing, and direct recycle is set up to solve the water-wastewater problem as a whole plant concept. Discharged water from each unit as well as the fresh feed are considered as sources of water, whereas units that accept water are considered as sinks. In this model, it embeds all potential configurations by allowing each source to be segregated, mixed, allocated to other units, and returned back to the process. This set of allocation equation is then combined with the process constraints and solved as an optimization problem to target minimum freshwater feed into the system and design the water network simultaneously. This optimization problem is formulated as a Non-Linear Programming (NLP) and solved by the high-level modeling language GAMS (General Algebraic Modeling System). Finally, a cases study of tapioca starch is implemented. A 13.22% reduction of freshwater usage is obtained.

KEYWORDS: wastewater minimization, water network, NLP, mass integration.

INTRODUCTION

The growing interest in environmental impact addresses the most serious challenges currently facing the chemical process industry. The activity so-called pollution prevention is not only the end of the pipe treatment, but the pollution can be prevented by earlier stages. Consequently, the holistic approach to pollution prevention presents the viewpoint of process integration which main pollution prevention can be embedded through out the sequences of unit operations. This concept clearly performs the cost effective approach to various process objectives. Two-main strategies are used to reduce the waste especially wastewater in the complex chemical process. They are[1]:

1. Source reduction includes any in-plant action to reduce the quantity or the toxicity of the waste at the source. Examples include equipment modification, design and operational changes of the process, reformulation or redesign of products, substitution of raw materials, and use of environmentally benign chemical reactions.

2. Recycle/reuse involves the use of pollutant-laden streams within the process. Typically, separation technologies are key elements in a recycle/reuse system to recover valuable materials such as solvents, metals, inorganic species, and water.

In this work, the focus is only on recycle/reuse of water through the chemical process as an integrated system. The mathematical formulation will be demonstrated by using a case study of starch manufacturing which in general uses tons of water and has a systematical processing.

METHODOLOGY AND IMPLEMENTATION

There are a lot of unit operations that require water to remove contaminant from the process streams. This water in turn becomes contaminated. To utilize water throughout the system, one simple method is water reuse. The discharged streams from any units can be reused in other units directly or it can be mixed with other discharged streams and then reused later.

This task is one kind of mass exchanged networks (MENs) problem which concerns the transfer of mass from **source** (stream that contains contaminants) to **sink** (unit that can accept contaminants). In order to minimize the amount of freshwater usage throughout the process system, one can maximize the possibility of water reuse from one operation to others. In mass exchanged problem, it cannot consider only the value of level of contaminants *eg* COD, BOD, TS, *etc*, therefore, with some streams cannot mix together. In order to embed all process constraints, it is of interest to formulate this mass integration problem in a systematic design which can target the minimum water flowrate and design network configuration simultaneously.

El-Halwagi and Garrison[2] introduced the problem of utilization of the discharged water from processes for segregation, mixing, reusing, and direct recycle. Since the aim of mass integration is at the optimal allocation of species or streams throughout the process. Instead of dealing with the detailed flowsheet of the process, a global mass allocation representation is presented. For each species there are **sources**, stream that carry that species, and **sinks**, units that can accept the species. Streams leaving the sinks become sources. Hence, sinks can also be generators of the target species.

Also sources can be mixed together and reuse. To determine the opportunities of reuse/recycle of each stream, a plot of flowrate or contaminant load versus its concentration is generated as shown in Fig 1; namely a source-sink mapping diagram

In Fig 1, the shaded circles represent sources, and the hollow circles represent sinks. Generally, the range of contaminant concentration and loading of each sink are limited by the process constraints. The intersection of the acceptable zone of sink and source provides the acceptable zone for reuse/recycle. Any source which lies within this zone can be directly reuse/recycle to that sink as can be seen from source "a" to sink "R" in Fig 1. Referring that streams mixing is allowable to feed prior to other source, source b and c can be mixed and reuse in sink R.

From the framework described in Fig 2, it contains all potential configurations by allowing each source to be segregated, mixed, allocated to other units, and returned back to the process. Typically, the process constraints limit the range of con-taminant concentration and load that each sink can accept. The task of optimization is to determine the flowrate and composition of each stream which is satisfied all those process constraints.

The concept of mass integration for segregation, mixing, reuse, and direct recycle was demonstrated by using the starch manufacturing.

Tapioca Starch Manufacturing

Tapioca or manioc starch is obtained from the tuberous roots of the manioc or cassava plant, which is one of the main products in Thailand. Basically manufacturing can be divided into four stages[3]:

1. Washing and peeling of the roots, rasping them and straining the pulp with addition of water.

2. Rapid removal of the fruit water and its soluble and replacing thus with pure water to prevent deterioration of the pulp. This stage includes sedimentation, washing of the starch in tanks, or on settling tables, silting, and in some of the medium and larger factories centrifuging.

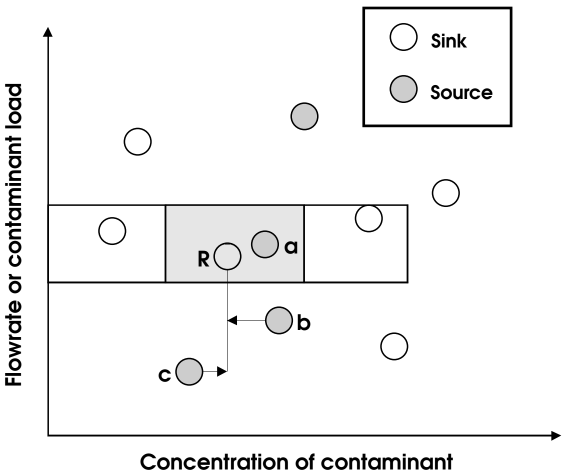

Fig 1. A source-sink mapping diagram.

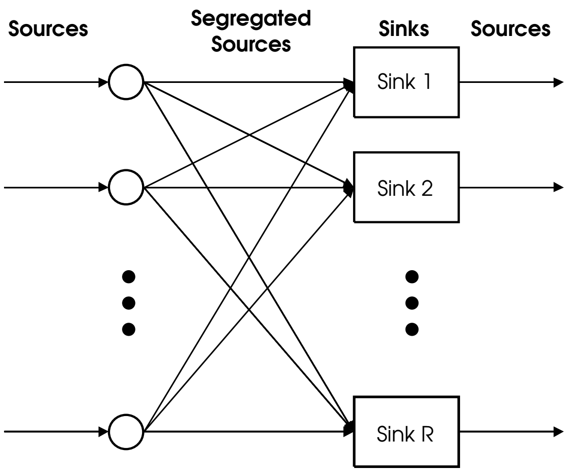

Fig 2. Mass integration framework for segregation, mixing, reuse, and direct recycle.

3. The removal of water by draining, centrifuging and drying.

4. Grinding, bolting and other finishing operations.

In the tapioca starch manufacturing, processes that consume water are washing, rasping, grinding, screening, and separating. For washing, rasping, and grinding process, water is used to wash the adhering dirt and added in peeling, rasping, and grinding process. Therefore, it does not need to use freshwater in these processes. After that the slurry is sent to screening process in order to separate the fiber and other insoluble particles such as protein, fat, *etc* Then the soluble particles are removed with water in the separating process.

In screening and separating processes, although the COD value is high in the discharged water, one important component of those chemicals is starch. In order to recover this amount of starch, the valuable discharged water can be reused. The criteria for selecting the streams to be reused are the COD value, amount of starch left and other physical properties such as the amount of protein. Next, another consideration of reusing water is which unit can accept this water. For the starch manufacturing, water reuse is not only the reduction of freshwater used but it can also recover the valuable starch product. Two major machines involved are screen and separator. In screen machine, large solid particles such as fiber, fat, *etc* are separated from small particles by centrifugal force. Hence, some starch can be lost with fiber because of the size and branches of fiber. Whereas in separating machine starch is separated from other lower density particles such as protein by centrifugal force. Because of the limited technical supports to represent how much water and what amount of contaminants (including starch) that can affect the efficiency of the operations, this work is based on the original process flowsheet of each plant.

Mathematical Model

In order to set up a starch model, mass balances must be made by using the following assumptions:

1. There are two main components in the manioc roots: starch and water. Other components will be treated as one component named others.
2. Amount or value of COD in mg/l is equal to the summation of amount of starch and others in mg/l.
3. The compositions of the starch loss in drying unit are the same as the dry starch product.

For the first assumption, it is sufficient to analyze only these components: starch, water, and others. For the second assumption, since COD is calculated from the amount of oxidizing agent used to completely oxidize the chemical substances in water. For the third assumption, after the wet starch is dried in a pneumatic dryer, it is sent to cyclone. Some starch loses in the cyclone. The composition of the lost starch is exactly the same as the dry starch product. Therefore, this assumption is reasonable.

To set up a model, the parameters and variables can be summarized as shown in Fig 3.

Additional assumptions are made in order to simplify the model. They are:

1. Only single contaminant is considered.
2. No equilibrium relation governs the distribution of contaminant in water.

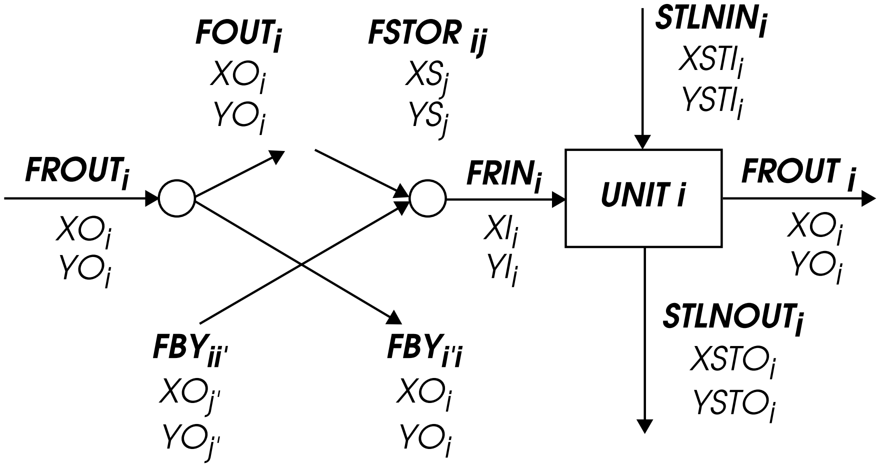

Fig 3. Flow diagram of the starch line and water line of each unit.

3. The efficiency of starch removal and COD removal of each unit are constant although the inlet concentration of any streams changed.

4. The flowrates of both starch line and waterline, are the same as the original flowsheet.

Basically, the indicator used to describe the property of wastewater is the value of COD. It acts like a single contaminant in waste stream, although there are many kinds of contaminants. Hence, the first assumption is reasonable. Since there is no limitation for starch to disperse in water, in other word, there is no equilibrium relationship between them. Therefore the second assumption is also applied.

For the third assumption, since the mass balances can be made, and the composition of each stream for normal operating condition is known, the efficiency of starch removal and COD removal of each unit can be calculated by

$$STEFF_i = \frac{\left[\left(STSTOUT_i\right)\left(STLNOUT_i\right)\right]}{\left[\left(STSTIN_i\right)\left(STLNIN_i\right)+\left(STRIN_i\right)\left(FRIN_i\right)\right]} \quad (1)$$

$$CODEFF_i = \frac{\left[\left(CROUT_i\right)\left(FROUT_i\right)\right]}{\left[\left(CSTIN_i\right)\left(STLNIN_i\right)+\left(CRIN_i\right)\left(FRIN_i\right)\right]} \quad (2)$$

The efficiency of each unit is held constant whether the compositions of the inlet streams have changed except in washing and drying unit. In washing unit, the composition of clean roots is held constant as in the original flowsheet. In drying unit, the composition of the starch loss and the dry starch product is the same.

For the last assumption, since there are no technical supports to represent how much water and what amount of contaminants (including starch) that can affect the efficiency of the machines. That is all the flowrates, both starch line and waterline, are the same as the original flowsheet.

Network Optimization

The utilization of the discharged water from processes for segregation, mixing, reusing, and direct recycle was formulated as a NLP problem. The solution of this NLP is the optimal allocation of species or streams throughout the process with minimum freshwater flowrate target. Prior to presenting the mass integration and its mathematical formulation, the following synthesis model are presented:

- Overall balance around splitter of each source R

$$FROUT_i - \sum_{i' \in R} FBY_{i'i} - FOUT_i = 0 \qquad i \in R \qquad (3)$$

- Overall balance around mixer of the inlet of each sink R

$$FRIN_i - \sum_{i' \in R} FBY_{ii'} - \sum_{j \in S} FSTOR_{ij} = 0 \qquad i \in R \qquad (4)$$

- COD balance around mixer of each source R

$$\left(FRIN_i\right)\left(YI_i\right) - \sum_{i' \in R}\left(FBY_{ii'}\right)\left(YO_{i'}\right) - \sum_{j \in S}\left(FSTOR_{ij}\right)\left(YS_j\right) = 0 \quad i \in R \quad (5)$$

- Starch balance around mixer of each source R

$$\left(FRIN_i\right)\left(XI_i\right) - \sum_{i' \in R}\left(FBY_{ii'}\right)\left(XO_{i'}\right) - \sum_{j \in S}\left(FSTOR_{ij}\right)\left(XS_j\right) = 0 \quad i \in R \quad (6)$$

- COD balance around each sink R

$$\begin{aligned}&\left(FRIN_i\right)\left(YI_i\right) + \left(STLNIN_i\right)\left(YSTI_i\right) - \left(FROUT_i\right)\left(YO_i\right) - \\ &\left(STLNOUT_i\right)\left(YSTO_i\right) = 0 \quad i \in R\end{aligned} \qquad (7)$$

- Starch balance around each sink R

$$\begin{aligned}&\left(FRIN_i\right)\left(XI_i\right) + \left(STLNIN_i\right)\left(XSTI_i\right) - \left(FROUT_i\right)\left(XO_i\right) - \\ &\left(STLNOUT_i\right)\left(XSTO_i\right) = 0 \quad i \in R\end{aligned} \qquad (8)$$

- Total freshwater feed

$$FFW = \sum_{i \in R, j \in S} FSTOR_{ij} \qquad (9)$$

- Efficiency limit (COD)

$$YO_i = CODEFF_i * \frac{\left[\left(YI_i\right)\left(FRIN_i\right) + \left(YSTI_i\right)\left(STLNIN_i\right)\right]}{\left[\left(CROUT_i\right)\right]} \qquad (10)$$

$$i \notin 'WASH', 'DRY'$$

- Efficiency limit (starch)

$$XSTO_i = STEFF_i * \frac{\left[\left(XI_i\right)\left(FRIN_i\right) + \left(XSTI_i\right)\left(STLNIN_i\right)\right]}{\left[\left(STLNOUT_i\right)\right]} \qquad (11)$$

$$i \notin 'WASH', 'DRY'$$

Then the optimization problem can be set up by minimizing

$$Z = FFW \qquad (12)$$

subject to the Equations 3 - 11 and all other constraints that come from the process flowsheet.

Case Study

According to Fig 4. The original process, there are four screens and three separators in this plant. The first three screens are used in the main process, while the remaining is used as a final screen to recover starch from pulp coming from those three screens. From Fig 4, the pulp from 'Screen 1', 'Screen

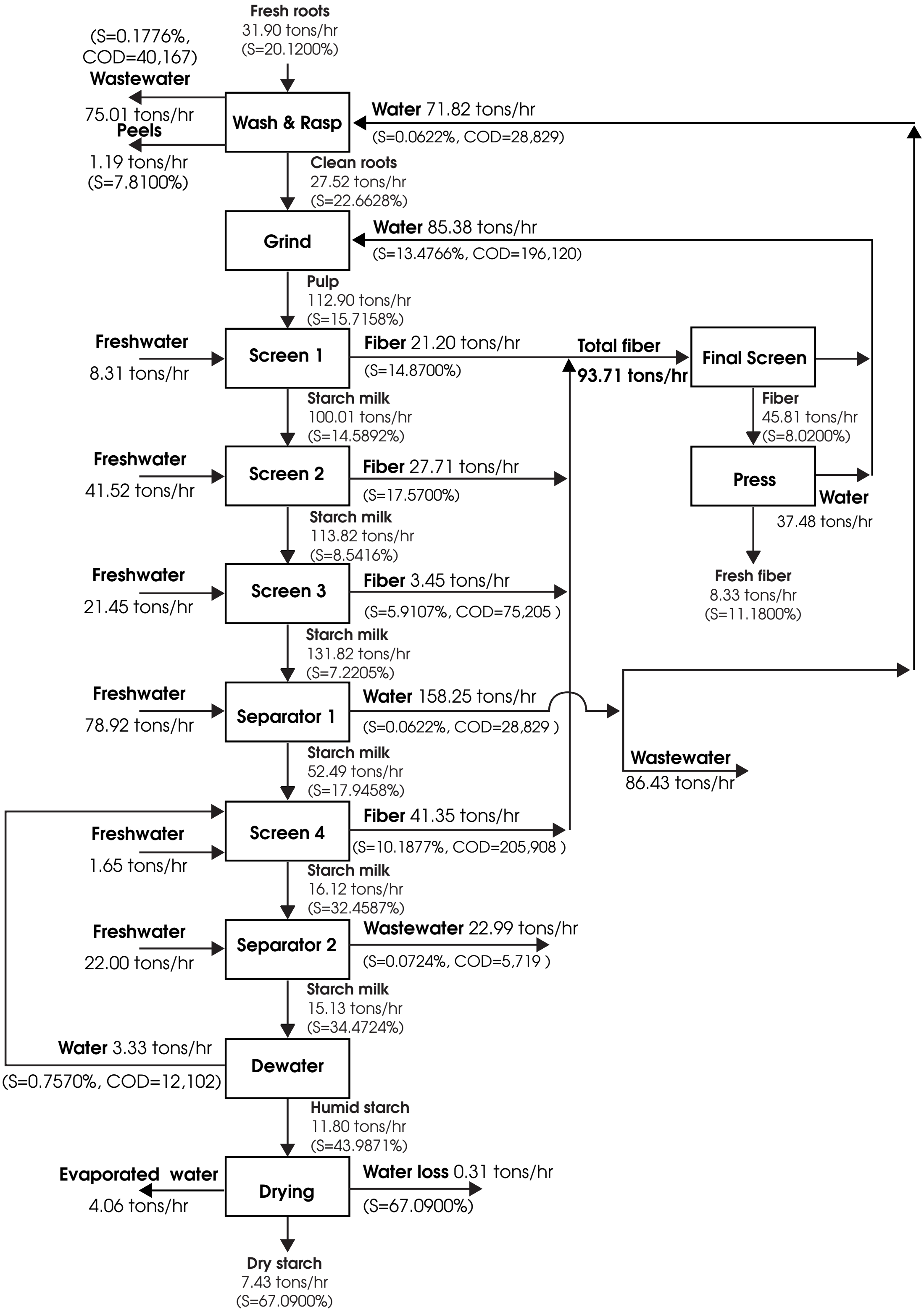

Fig 4. Flowsheet for the manufacturing of tapioca starch Plant before improving (S = % of starch, COD = COD value in mg/l).

2', "Screen 3', and 'Screen 4' contain high value of starch, they are sent to the 'Final Screen' to recover the starch. After the pulp has been separated in the 'Final Screen', filtrate, which is rich of starch, is returned to the grinding process, while the fiber is sent to 'Press' to recover water, and the 'Fresh Pulp' is sold as a cattle food.

In separating process, discharged water from the 'Separator 1' is quite high in COD, but the main indicator of this stream is the value of Total Kjeldahl Nitrogen or TKN. This TKN indicates that the amount of protein of this stream is quite high. And also most of cyanide, which is the undesired component of the starch product, is separated in this stage. Therefore, this discharged water is not suitable to reuse in any process except for the washing and rasping. In the other separating machines, the property of discharged water is suitable to be reused. For starch plant A, the following sets are defined:

$$R = \left\{ \begin{array}{l} i|'Wash','Grind','Screen1','Screen2','Screen3','Sep1', \\ 'Screen4','Sep2','Dewater','Dry','Final Screen','Press' \end{array} \right\}$$

$$S = \left\{ j\,|\,'Fresh' \right\}$$

In order to set up an optimization program, all the process constraints have to be embedded as follows:

1. Any stream cannot recycle back to its process in order to prevent the building up of con-taminants.
2. Discharged water from 'Screen 1', 'Screen 2', 'Screen 3' and 'Screen 4' are sent to recover starch in the 'Final Screen'.
3. Discharged water from 'Final Screen', which is rich of starch, is returned to 'Grinding unit' only.
4. The discharged water from 'Separator 1' cannot be reused in any unit except in wash-ing process since this water contains high protein.
5. Water from 'Dewater' is returned to 'Screen 3' only (the same as in the original flowsheet).
6. The discharged water from 'Press' can only be returned to 'Grinding unit' (the same as in the original flowsheet).
7. Freshwater will not add to 'Grinding unit', 'Dewater', 'Dry', 'Final Screen', and 'Press'. Therefore, the upper bound for the inlet COD of these units can be set quite high in order to receive the reuse water from other units.
8. Discharged water from 'Washing unit' cannot be reused in any other units.
9. In the starch plant, the amount of con-taminants is decreased from upstream to downstream units. Hence, water can be reused from downstream unit to the upstream unit. Finally, the last unit receives only freshwater. The following stream compositions (COD) are bounded:

$$0 \le XI('SEP1') \le 0.00$$
$$0 \le XI('SEP2') \le 0.00$$
$$0 \le XI('Screen1') \le 0.01$$
$$0 \le XI('Screen2') \le 0.01$$
$$0 \le XI('Screen3') \le 0.00$$
$$0 \le XI('Screen4') \le 0.013$$
$$0 \le XI('Final\,Screen') \le \infty$$
$$0 \le XI('Press') \le \infty$$
$$0 \le XI('Wash') \le \infty$$
$$0 \le XI('Grind') \le \infty$$

where the unit of COD is in milligram per liter.

These process constraints which are in GAMS input form are then added to the allocation equations (Equations 3 to 11) and are considered as Non-Linear Programming constraints for the freshwater flowrate minimization. Fig 5 shows the solution of this problem.

Results and Discussions

According to Fig 4, there are three units that discharge water to the biological treatment system: 'Separator 1', 'Separator 2', and 'Washing unit'. The discharged water from 'Separator 1' and 'Washing unit' cannot be reused, since they contain high values of COD and TKN. Also the discharged water from 'Press' is not suitable to be reused in any units except the 'Grinding unit' because of its high value of total solid. Therefore, only one discharged stream from 'Separator 2' can be segregated. This action can reduce amount of freshwater usage by 22.99 tons/hr and reduce amount of wastewater generation by 22.99 tons/hr as well.

Since the Non-Linear optimization problem cannot give a unique solution, although the Non-Linear Programming is implemented. There are three solvers in GAMS that can solve a NLP optimization: CONOPT2, CONOPT, and MINOS5. The weak point of NLP problem is that the solution depends upon the starting points and the path of solving. In GAMS, the paths of solving depends upon the solvers even in the same starting point. The optimal solution cannot be guaranteed, and if a solution is reached, it can only be considered as a local optimum.

There are three alternatives presented here as shown in Figs 5, 6 and 7, which are solved by CONOPT2, CONOPT, and MINOS5, respectively.

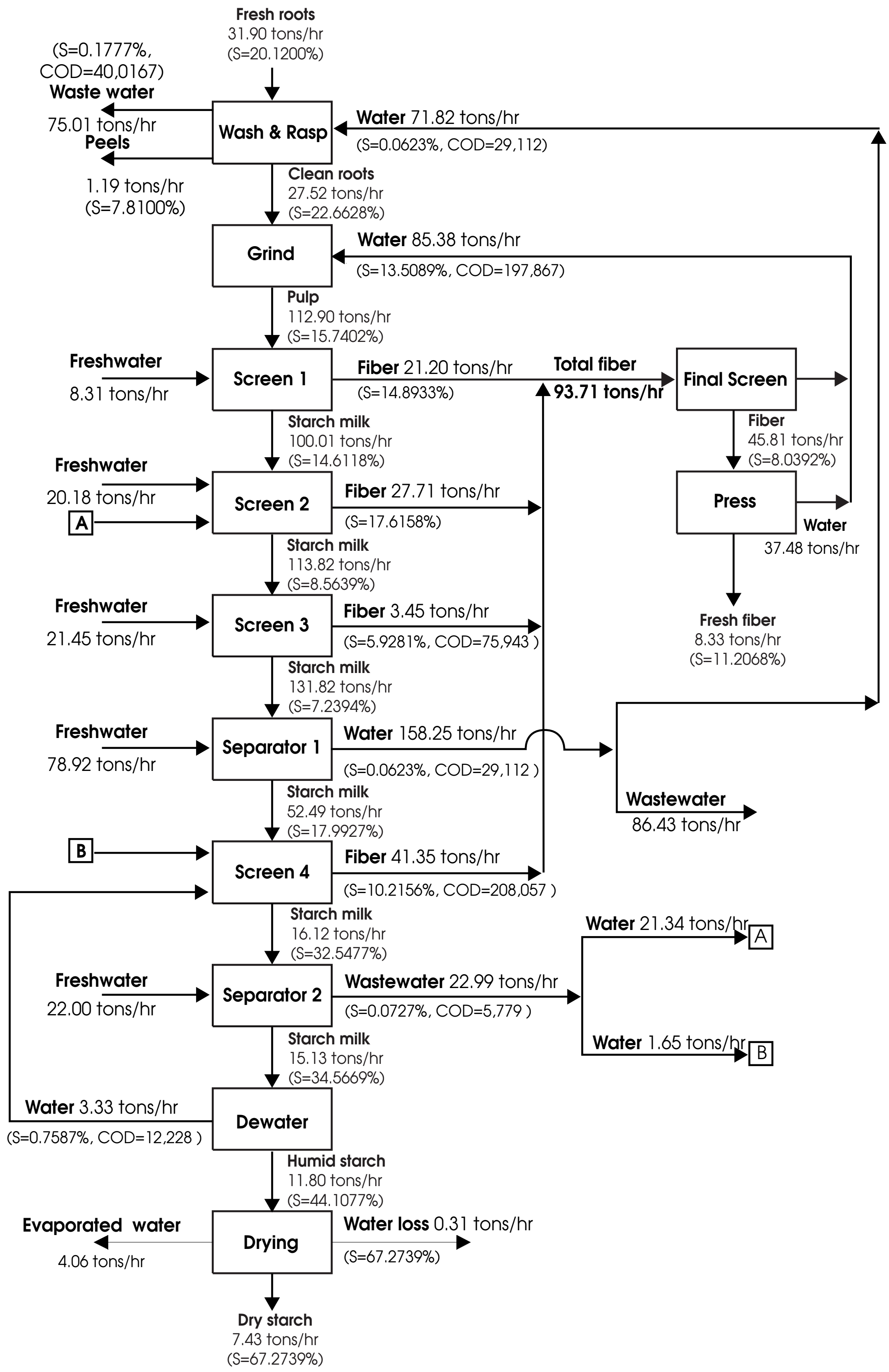

Fig 5. Flowsheet for the manufacturing of tapioca starch Plant alternative 1 after improving (S = % of starch, COD = COD value in mg/l).

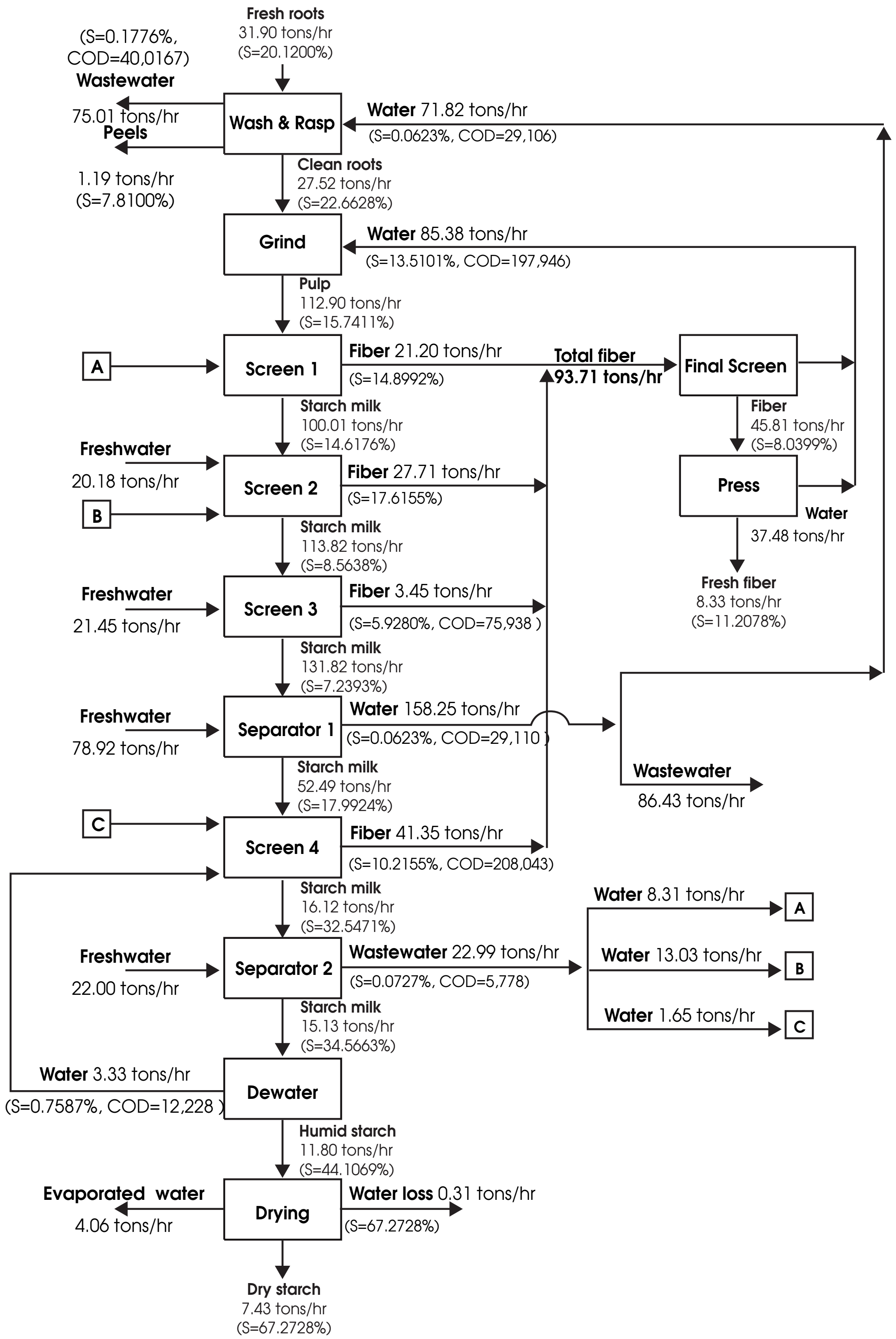

Fig 6. Flowsheet for the manufacturing of tapioca starch Plant alternative 2 after improving (S = % of starch, COD = COD value in mg/l).

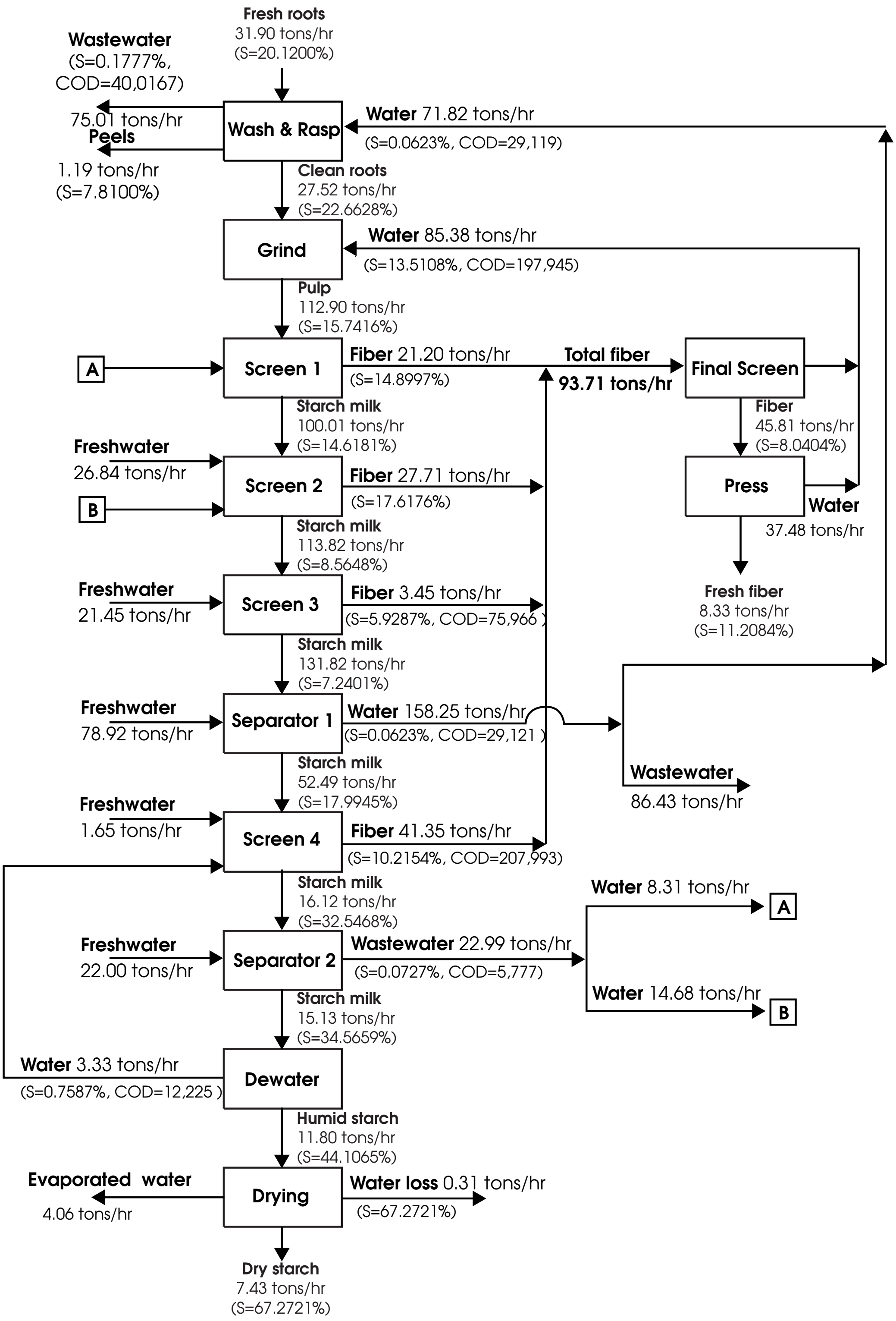

Fig 7. Flowsheet for the manufacturing of tapioca starch Plant alternative 3 after improving (S = % of starch, COD = COD value in mg/l).

All of them give the same water reduction with three approaches. At this stage, the economical trading off must be taken to evaluate between the freshwater saving and the investment cost for piping and pumping in order to give the best alternative. Since this work is based on the original flowsheet, especially, the flowrate of stream input and output to any unit. It must be worth to find out the efficient range of water flowrate and its concentration inlet in order to utilize the water usage throughout the system. For example, the inlet flowrate of water to 'Separator 1', 78.92 tons/hr, is quite high comparing to other separators, and the property of the discharged water from this 'Separator 1' is not suitable to be reused in any other units except in the washing process. It is obvious that when the efficient range of water flowrate and its concentration are known, one can reduce the amount of water usage more effectively.

Hence tapioca starch is one kind of food manufacturing, the reuse of wastewater should be considered in terms of the quality of starch. When starch is reused in the system, it can be degraded depending on its age. It must be further studied to find out how many hours it can be recycled in the system.

The main discussion shows the application of mass exchanger network to retrofit the existing process and hits the concept of cleaner technology. The technique forms a non-linear problem which usually has many local optimal solutions. Basically the supplement information such as additional investment cost needs to be investigated in order to polish for the best operational practice.

CONCLUSION

A mass integration for segregation, mixing, reusing, and direct recycle is generated to solve the water-wastewater problem as a whole plant concept. Discharged water from each unit as well as the fresh feed are considered as of water, whereas units that accept water are considered as **sinks**. In this model, it embeds all potential configurations by allowing each source to be segregated, mixed, allocated to other units, and returned back to the process. This set of allocated equation is then combined with the process constraints and solved as an optimization problem to target the minimum freshwater feed to the system and to design the water network simultaneously. This optimization problem is formulated as a Non-Linear Programming by using the high-level modeling language GAMS. Finally, a case study of the tapioca starch plant are implemented. Freshwater usage and wastewater generation can be reduced to 13.22%.

In this work, only single contaminant is addressed. The process constraints can be taken into account such as processes with water loss or gain, fixed water flowrate constraints, etc. In principal, the solution of non-linear optimization is not unique even with Non-Linear Programming implementation. Therefore, the expected result from this water-wastewater minimization approach is also under this situation. There are more than one water network configurations that satisfy the same objective value. Hence, it must be traded off between those alternatives for both variable cost and fixed cost in order to achieve the best solution.

NOMENCLATURE

BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
TKN	Total Kjeldahl Nitrogen
NLP	Non-Linear Programming

1. Indices:

i, i'	units
j	fresh source *ie* freshwater

2. Sets

R, RP	units
S	freshwater

3. Parameters

$STLNIN_i$	inlet flow of starch line of each unit i in tons/hr
$STLNOUT_i$	outlet flow of starch line of each unit i in tons/hr
$FRIN_i$	inlet flow of water line of each unit i in tons/hr
$FROUT_i$	outlet flow of water line of each unit i in tons/hr
$STSTIN_i$	fraction of starch in starch line inlet of each unit i in milligram per liter
$STSTOUT_i$	fraction of starch in starch line outlet of each unit i in milligram per liter
$STRIN_i$	fraction of starch in water line inlet of each unit i in milligram per liter
$STROUT_i$	fraction of starch in water line inlet of each unit i in milligram per liter
$CSTIN_i$	COD inlet of starch line of each unit i in milligram per liter
$CSTOUT_i$	COD outlet of starch line of each unit i in milligram per liter

$CRIN_i$	COD inlet of water line of each unit i in milligram per liter
$CROUT_i$	COD outlet of water line of each unit i in milligram per liter
$STEFF_i$	efficiency of each i to remove starch
$CODEFF_i$	efficiency of each i to remove COD
XS_j	starch composition of fresh sources S
YS_j	COD composition of fresh sources S
$IR_{ii'}$	binary value used to indicate the potential of water stream from unit i' to be reused in unit i
$UPCOD_i$	upper limit of the inlet COD of the water line of each unit I

4. Variables

Z	objective variable
FFW	total freshwater flowrate in tons/hr
FBY_{ii}	flowrate from one unit to others i in tons/hr
$FSTOR_{ij}$	flowrate of stream of *j* to *i* in tons/hr
$FOUT_i$	flowrate of outlet stream of unit i to treatment process in tons/hr
$XSTI_i$	fraction of starch in starch line inlet of each unit *i* in milligram per liter
$XSTO_i$	fraction of starch in starch line outlet of each unit *i* in milligram per liter
XI_i	fraction of starch in water line inlet of each unit *i* in milligram per liter
XO_i	fraction of starch in water line inlet of each unit *i* in milligram per liter
$YSTI_i$	COD inlet of starch line of each unit *i* in milligram per liter
$YSTO_i$	COD outlet of starch line of each unit *i* in milligram per liter
YI_i	COD inlet of water line of each unit *i* in milligram per liter
YO_i	COD outlet of water line of each unit *i* in milligram per liter

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