FLOWSHEETING APPROACH FOR BATCH AND SEMI-CONTINUOUS PLANTS

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ABSTRACT

Design of plants consisting of batch and semi-continuous units involves specification of the capacity of each processing stage, the number of parallel units at each processing stage and the operating schedule. In this paper, a set of design guidelines which allows taking into account of features likely to be encountered when designing for the developing countries environment is proposed. The approach is illustrated by the design of a flowsheet for small scale village level sugar production plant.

INTRODUCTION

Small scale process plants are increasingly important in developing countries. They help these countries to achieve social and economic development. One of the important step towards development of a successful process plant is the development of an appropriate flowsheet.

A distinction can be made between continuous, steady state process plant versus batch and semi-continuous plant. Continuous, steady state plants requires deciding the type of units for each processing stage and their inter-connections, their sizes and shape so as to produce required products at required quality and rate, and at minimum cost. An approach for designing such a plant has been dealt with by Kaunde[1,2].

This paper aims at dealing with the design of batch and semi-continuous plants.

PROBLEM DEFINITION

Batch operations are defined as those characterised by processing time and do not involve simultaneous feed and removal of by-products. Semi-continuous operations are those characterised by steady state continuous processing rate which can also run with periodic start up and shut downs [3]. Batch and semi-continuous stages can further be characterised into those for production of single product or several (multi-product and multi-purpose plant) products. In multi-product plants all the products produced in the plant follow the same sequence and typically the plant is operated in a series of single product campaigns. In multi-purpose plant each product has its own distinct processing sequence and employs the processing units in different combinations as such several products may be produced concurrently [4] .

Batch and semi-continuous operations have received increasing important in recent years due to the growing interest of chemical industries of developed countries in the production of high value added chemical products. As noted by Yeh and Reklaitis[5] these modes of operation are suitable for these type of complex materials because they can be structured to handle several products whose individual production requirements are generally not large enough to justify construction of dedicated plants.

In contrast, processing of agricultural based raw materials into their finished product would normally employ different processing units and follow different processing stages. It is therefore reasonable to assume that single product plants rather than multi-purpose or multi-product plants will remain to be a prominent feature for small scale plants in developing countries.

The problem of designing a flowsheet for single product batch and semi-continuous plant requires specification of optimum capacity of each unit, the number of parallel units at each stage, capacity of any intermediate material store and the operating schedule.

Several authors have addressed this problem. Ketner[6] and later Loonakar and Robinson[7] provides design method that uses ordinary calculus to establish minimum equipment cost. Takamatsu et al.[8] provides design methodology of a plant consisting of batch stages and intermediate material stores but without taking into account the effect of semi-continuous processing stages. Knopf et al.[3] introduced semi-continuous processing stages and illustrated the significance of energy cost in addition to capital cost in the batch and semi-continuous plants. Yeh and Reklaitis[5] proposes some heuristics that may be employed to work out the number of parallel units at each processing stage and capacities of processing unit for single product. Also a set of synthesis rules for selecting structural features such as consecutive tasks to me merged or spit have also been proposed.

As an extension to the existing design methods, this paper aims at proposing an approach which allows consideration of features that are likely to be met when designing for the developing country environment.

PROPOSED DESIGN APPROACH

The proposed approach consists of three basic steps as follows;

Step 1. Decompose the process into sub-processes
In some processes we can find batch stages with relatively long cycle time than the processes upstream and downstream. Crystallisation of sugar is one such example. This process may last for several days while crushing and evaporation processes upstream and centrifuge downstream have shorter cycle times which allows several batches to be completed during one working day. The batch unit with relatively longer cycle time may also serve as material store. This provides a larger flexibility in the design of stages before and after the batch stage. The stage(s) upstream may be said to form one sub-process and those down stream form another sub-process. With larger number of processing stages in a sub-process several other sub-processes may be defined in the same way. The batch stage separating any two sub-processes is considered as a sub-process of its own. Each sub-process can then be designed independently, such that over a given time interval the sub-process must handle enough material corresponding to the production requirements of the final product.

Step 2. Optimization of sub-process
With a sub-process containing more than one processing stage alternative structural configurations may be derived by either adding parallel units or

inserting intermediate material stores. These are the two means normally used to reduce the limiting cycle time and therefore increase equipment utilization.

At this stage therefore simple mathematical models can be used to estimate economic objectives for the proposed alternative structural configurations.

For a batch stage the capacity V of batch unit required to meet production target Q is given by;

$$V = \frac{Si.Q}{P.B} \qquad (1)$$

The capacity factor Si as defined by Rippin[9] is the quantity (weight, volume or any other measure of capacity) needed during task i to process enough material to make one unit of final product at the end of the batch.

Similarly for semi-continuous stage, the processing rate, R is given by;

$$R = \frac{Si.Q}{Ts.P.B.} \qquad (2)$$

Where a pump is required in the process, its cycle time may be related to its pumping rate by;

$$Tp = \frac{Si.Q}{r.B} \qquad (3)$$

If the six tenth rule for calculating cost is assumed we have capital cost of a unit given by;

$$CostA = CostB\left[\frac{capacityA}{capacityB}\right]^{0.6} \qquad (4)$$

A suitable operating (energy) cost function may be assumed. For example the energy cost of batch unit, Eb may assume an equation of the type;

$$Eb = P.B.Tb.Yd.p.\left[\frac{V}{V'}\right]^{w} u \qquad (5)$$

Likewise for semi-continuous unit the energy cost, Esc may be given by;

$$Esc = P.B.Ts.Yd.p\left[\frac{R}{R'}\right]^{w} u \qquad (6)$$

In this approach it is assumed that the cycle time of batch unit(s) in a sub-process is fixed by the kinetics of the process, whereas the cycle time of semi-continuous units can be chosen, hence is a design variable. The governing equations for estimating the cycle time Ts of a semi-continuous unit will depend on the structure and schedule of the sub-process. The above set of equations together with the cycle time of semi-continuous units should enable evaluation of the economic objectives (capital, energy and/or annualized cost) for the alternative structural configurations, and the best alternative can be identified.

It should be pointed out at this stage that the above equations can easily be coded into subroutines of a computer program such as BASIC or FORTRAN and repeatedly used for calculating different processing units.

Step 3. Merging up of optimized sub-processes.
As used in this design approach, optimization of a sub-process refers to the size of units and structure (parallel units) that gives the best value of the specified economic objectives. If the condition stated in step 1 is met, i.e. each sub-process must on a given time interval handle enough material corresponding to the production requirements of the final product, then optimizing individual sub-processes corresponds to optimizing the whole plant. In this step (i.e. step 3) therefore individual sub-processes are merged to define the overall flowsheet.

THE CASE STUDY

Equipment for production of crystalline sugar at small scale (about 300 kg per 8 hours working shift) has been developed in Tanzania [10]. Cane crushing is done in a system of three rollers. Juice concentration is achieved in an open pan evaporator system consisting of a cascading three pan furnace. Transformation of syrup into massecuite (a mixture of sugar crystals and molasses) is carried out in a crystallizer system comprising of U-shaped vessels. Separation of sugar crystals and molasses is carried out in a batch type centrifuge, in which the main operations - feeding, washing and sugar removal are all done manually. Sun drying is a technique used at present for drying the wet sugar, although a rotary drier is being developed for this purpose.

Except for the evaporation process which uses bagasse as its energy source all other equipment in the system are coupled to a drive unit which is driven by a diesel engine of about 20 kW. The crusher is the only semi-continuous unit in the process and the rest are batch units.

The flowchart showing mass balance round the sugar plant is as shown in Fig 1.

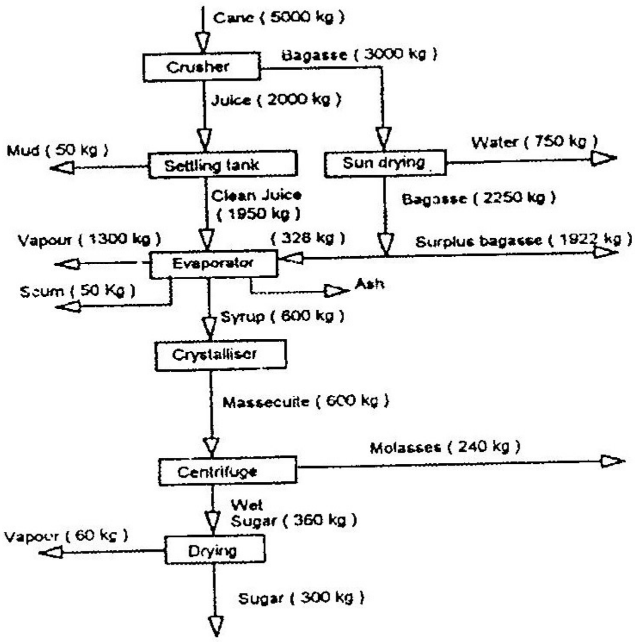

Fig. 1 Mass balance for the sugar plant

APPLICATION TO THE CASE STUDY

Step 1. Decompose the process into sub-processes

With reference to the existing small scale sugar plant, crystallisation is a processing stage with the longest cycle time lasting for 3 days. This stage therefore separates the crusher and evaporator sub-process upstream from the centrifuge sub-process downstream (Fig 2).

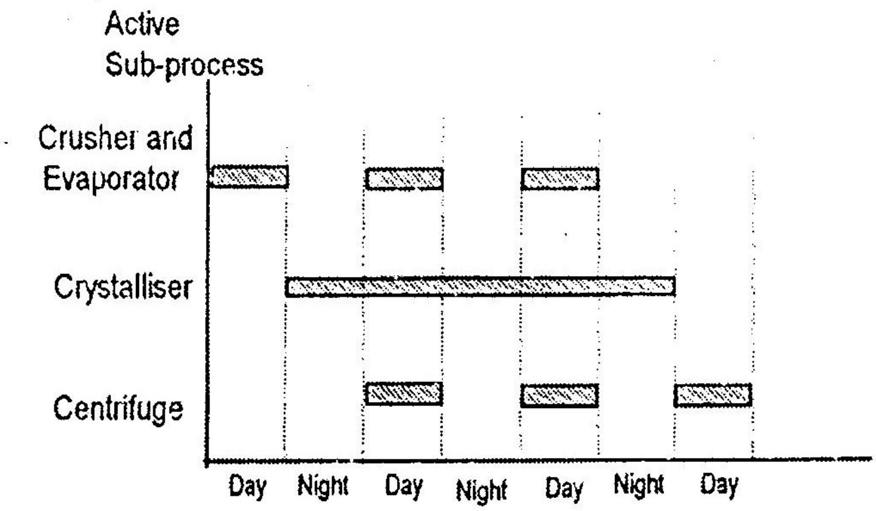

Fig. 2 Sub-processes for the sugar plant

Step 2. Optimization of sub-process

Crusher and evaporator sub-process.
The crusher and evaporator sub-process is the only one containing a batch and semi-continuous stage. The cycle time of the evaporator is fixed by the kinetics of the process, and for simplicity we assume that is independent of the batch size. On the contrary cycle time of the crusher is not fixed and should be chosen taking into account of the daily production requirements and the economy of the sub-process.

Four structural configurations and operating schedules (referred to for simplicity as "schedules") are possible. These schedules and their corresponding governing equations for estimating cycie time of crusher, capacity of each evaporator unit, and capacity of intermediate material storage vessel are as shown in Figures 3 to 6.

Note that in deriving these schedules the following assumptions were made;

- evaporation stage (batch stage) can have parallel units but not the crushing stage (semi-continuous),
- where parallel evaporators are to be used, no material intermediate storage vessel should be supplied, and
- parallel evaporator units must each complete the same number of

batches in a given shift, so as to ensure maximum equipment utilisation.

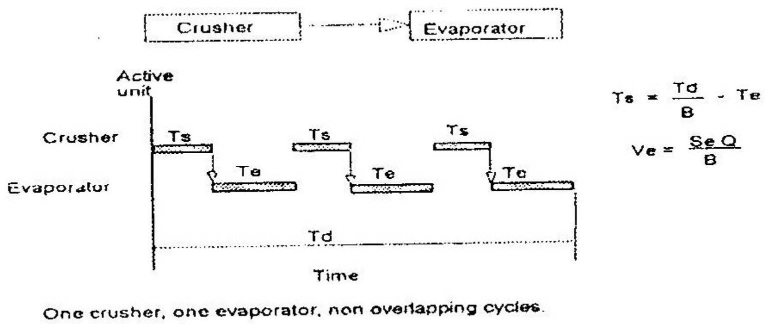

Fig. 3 Crusher, one evaporator, sub-process (Schedule no. 1)

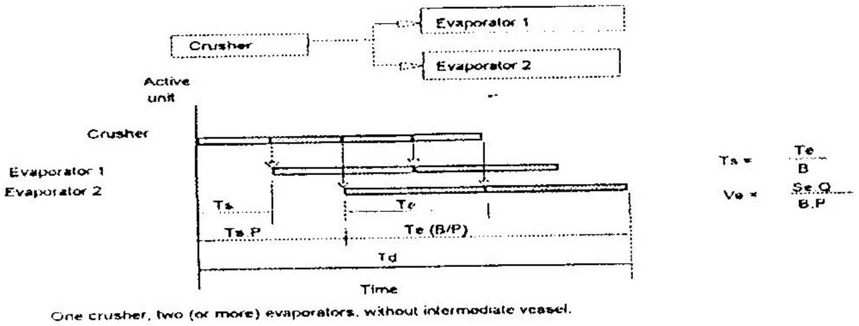

Fig. 4 Crusher and evaporator sub-process (Schedule no. 2)

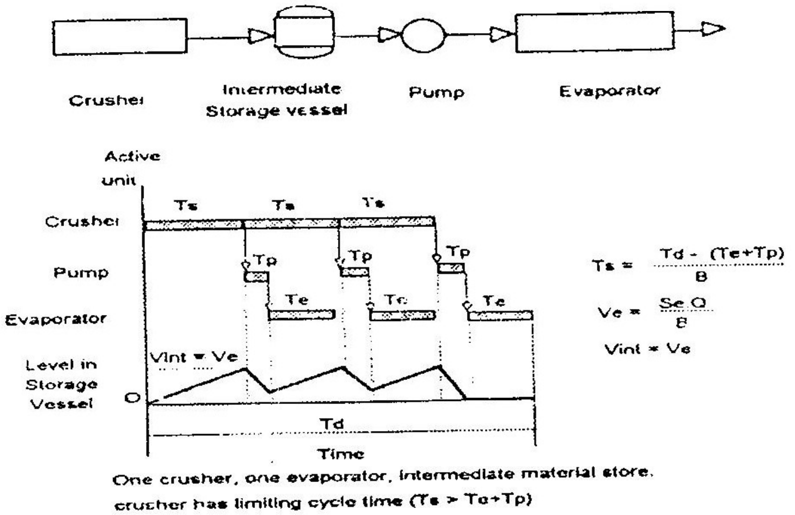

Fig. 5 Crusher and evaporator sub-process (Schedule no. 3)

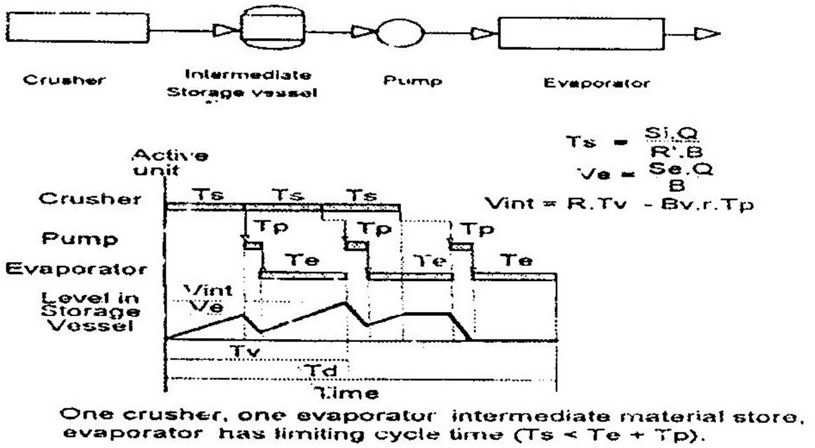

Fig 6 Crusher and evaporator sub-process (Schedule no. 4)

Schedule 1, 3 and 4 each have one evaporator, but schedule 1 differ from the other two as the former does not include material intermediate store. The difference between schedule 3 and 4 lies on the limiting cycle time processing stage. In each of these three schedules, the number of batches processed per day is a free variable that can be altered in search for equipment capacities that will give minimum value of specified economic target.

Crystallizer sub-process

Three crystallizer sets are required by the crystallization process for continuous operation, i.e. cycle time of crystallisation process is 3 days. Thus each day one crystallizer set is filled with syrup, while the set with fully grown sugar crystals is being depleted as massecuite is processed by the centrifuge. However, each crystallizer set may contain several vessels in parallel. The number of parallel vessels is a design variable which can be varied in search for optimum capacity of each vessel.

Centrifuge sub-process.

This is another sub-process containing a single batch stage. With this sub-process, the number of batches is a search variable for establishing the optimum capacity of centrifuge basket.

Step 3. Merging up optimized sub-processes.

The results for the best schedules of the crusher/evaporator sub-process are combined with those for crystallizer and centrifuge, and together they define the optimum flowsheet.

RESULTS

Using the set of data shown in Table 1 as the design basis the final results of the optimum flowsheet are as shown in Table 2. Table 3 shows the performance of the existing plant. The savings as a result of optimizing this plant according to the proposed method are as tabulated in Table 4.

Table 1 Design basis for sugar plant

Q	Td	Yd	Y	Tp
Kg/day	min	days	Years	kg/min
300	480	105	5	400

	Cycle time	Si	Capacity B	p	Cost B	u
		wt/wt		kW	Tsh.	Tsh/kWh
Crusher	variable	16.7	14.2 kg/min	7.5	900000	7
Evaporator	80 min.	6.5	162.5 kg/batch	205	450000	0.24
Crystalliser	3 days	2	600 kg/batch	12	217000	7
Centrifuge	10 min.	2	25 kg/batch	7.5	700000	7.5
Storage vessel	-	-	200 kg juice	-	50000	-

Table 2 Flowsheet specifications and costs for the optimised sugar plant

	Crusher	Storage	Evaporator	Crystallizer	Centrifuge	
Units in parallel	1	1	1	3	1	
Capacity of unit	13 kg/min	400 kg	487 kg	600 kg	13 kg	
Cycle time	100 min	-	80 min	3 day	10 min	
Total batches/day	4	-	4	1	48	
						Total cost
Capital (Tsh)	836200	85300	869900	651000	461800	2904200
Energy (Tsh/yr)	32800	-	74000	635000	23600	765400
Annual (Tsh/yr)	200000	17100	248000	765200	116000	1346200

Table 3 Flowsheet specifications and costs for the IPI sugar plant

	Crusher	Storage	Evaporator	Crystallizer	Centrifuge	
Units in parallel	1	1	2	3	1	
Capacity of unit	14 kg/min	200 kg	163 kg	600 kg	25 kg	
Cycle time	30 min	-	80 min	2 days	10 min	
Total batches/day	12	-	12	1	24	
						Total costs
Capital (Tsh)	900000	50000	960000	650000	700000	3260000
Energy (Tsh/yr)	33000	-	88800	635000	22000	779000
Annual (Tsh/yr)	213000	10000	280800	765000	162000	1431000

Table 4 Comparison between optimised and existing IPI plant

	IPI Plant	Optimum plant	Savings (Tsh)	Savings in %
Capital (Tsh)	3260000	2904300	35500	11%
Energy (Tsh)	779000	765500	13400	2%
Annual (Tsh)	1431000	1346200	84600	6%

CONCLUSION

An approach for designing a flowsheet consisting of batch and semi-continuous plants has been proposed. The proposed approach introduces a concept of sub-processes which can be optimized independently. The sub-processes are easier to handle and uses simple mathematical formulae for calculating capacities of process units and related costs. The optimum flowsheet is then formed by merging the individual sub-processes.

Different techniques and data for estimating capital and energy costs for the two plants (existing sugar plant and optimised plant) have been used. Although these data should be treated with caution, economic comparisons suggest that there could be some savings as a result of optimizing the sugar plant using the proposed approach.

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NOMENCLATURE

B	number of batches per day treated by process unit.
Bv	number of evaporation batches treated in time Tv.
E	energy (operating) cost of unit per year, TSh/year*.
Q	production capacity of finished product, kg/day.
P	number of units in parallel.

p	power consumption of base unit, kW
R	processing rate of a semi continuous unit, kg/min.
R'	processing rate of reference semi-continuous unit, kg/min.
r	pumping rate, kg/min.
Si	capacity factor of processing stage i, wt/wt.
T	cycle time of unit, min..
Td	plant operating time per day, min.
Te	cycle time of evaporator, min.
Tp	cycle time for pump, min.
Ts	cycle time of crusher, min.
Tv	time for the level in intermediate vessel to reach maximum, min.
u	unit cost of energy, TSh/kWh.
V	capacity of batch unit, kg.
V'	capacity of evaporator, kg.
Ve	capacity of evaporator, kg.
Vint	capacity of intermediate storage vessel, kg.
w	energy cost exponent, dependent on type of unit.
Y	plant life, years
Yd	number of working days per year, days.

* [US$ 1 = 450 Tsh approximately].

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