Energy Saving And Production Enhancement Through Scheduling Optimization Of Displacement Batch Digesters

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ABSTRACT

Displacement batch digester house for pulp production involves many digesters sharing common resources. In addition to this, since the digesters interact with each other in terms of using the hot liquors from previous batches, the problem of scheduling becomes a challenging task. The objective of scheduling optimization, in such cases, is to reduce the idle waiting time between various phases of the digesters so that this time can be used for production maximization and/or energy minimization. This study provides mathematical programming based optimization models and computational results for short-term scheduling of displacement batch digesters in a pulp industry. The scheduling problem involves development of an optimal solution in terms of batch's start and end times that yield the best sequence of operations in each of the batch digesters sharing common resources. The constraints are imposed on meeting the demand of pulp production within a specified time horizon. The problem comprises of both fixed-time and variable time durations of the tasks, different storage policies for states: zero-wait and finite wait times; and handling of shared resources. The scheduling problem is formulated using a state-task-network (STN) representation of production recipes, based on discrete time representation. This results in a mixed-integer linear programming (MILP) problem which is solved using GAMS software. Various case studies involving parallel digesters in multiple production lines are considered to demonstrate the effectiveness of the proposed formulation.

Introduction

Displacement batch cooking has evolved as an energy efficient alternative to the conventional batch cooking for Kraft pulping. This is achieved by storing the hot used liquor from the previous batches in the storage tanks and subsequently using the stored liquor for the next batches, thus, leading to energy recovery. In addition to this, a displacement batch digester house comprises of many digesters sharing the same resources. This poses a challenging task while the operation of displacement batch digesters is scheduled. Manual/heuristic ways of scheduling, in such cases, often results in idle waiting times with one or more digesters in the waiting phase. This has huge impact on the productivity and energy consumption in the digester house. With this motivation, in this work, we develop a State-Task-Network (STN) based, discrete time formulation for short-term scheduling of parallel displacement batch digesters attached to multiple production lines with resource constraints. Computational results involving several case studies are presented to demonstrate the effectiveness of the proposed methodology.

Literature Review :

Hvala *et al.* [1] addressed online scheduling of nine Conventional Batch Digesters operating in two parallel production lines under common resource limitations. They proposed a solution method based on a heuristic algorithm combining neighborhood search technique and linear programming. Later, Castro *et al.* [2] developed a discrete-time Resource-Task-Network (RTN) based formulation for scheduling of a resource constrained four batch conventional digester system leading to a mixed-integer linear programming (MILP) model. For estimating the durations of heating tasks, they used a separate process model a distributed heterogeneous dynamic model. They concluded that the bottleneck was in the steam availability and an increase in the total available steam is significant for improving the productivity. In general, the scheduling optimization solution has been attempted for variety of problems using state task network (STN) as well as resource task network (RTN) representation using both the discrete as well as continuous time formulations. A comprehensive review of these two approaches is given by Mendez et al. [3]. However, to the best of our knowledge, short-term scheduling of displacement batch digesters has not been attempted in the literature.

Results And Discussions :

Here we present the results for a configuration involving 5 digesters in 2 lines (3 in line 1 and 2 in line 2). However, using the generic strategy adopted, the solutions can be adapted easily for a configuration involving more number of digesters in multiple lines. The test cases are verified with respect to different initial amount of material in tank, different availability of steam as well as for different production targets. *Note that the values reported in this document are normalized with respect to the reference values so as not to disclose the actual values.*

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Table 1: Case studies considered in this study

Cases	Objective	Bounds on Level	Initial Amount of HBL1*	Max Bound on steam flow	Time Horizon
1	Max Production	20-80	60	2	7
2	Max Production	20-80	60	1.5	7
3	Max Heating and Cooking Time	20-80	60	2	7
4	Max Heating and Cooking Time	20-80	60	1.5	7
5	Max Production	20-80	30	2	7
6	Max Heating and Cooking Time	20-80	30	2	7
7	Max Production	20-80	60	2	18
8	Max Heating and Cooking Time	20-80	60	2	18

* Initial amount of HBL2, IL is assumed to be 60 for all the cases.

The results of various test cases are described below. The details of all these test cases are described in Table 1. In all these cases, it is assumed that WL is always available in the tank and the steam required for heating WL upto the temperature required in WL tank is 1 unit. Whenever there is transfer of HBL 2 from HBL Tank 2 to impregnation liquor tank, there is heat transfer to the WL and the steam requirement is reduced accordingly.

Fig. 1 shows results for a case 1 involving maximization of production for a given time horizon (7 time units). In this case, it can be seen that for

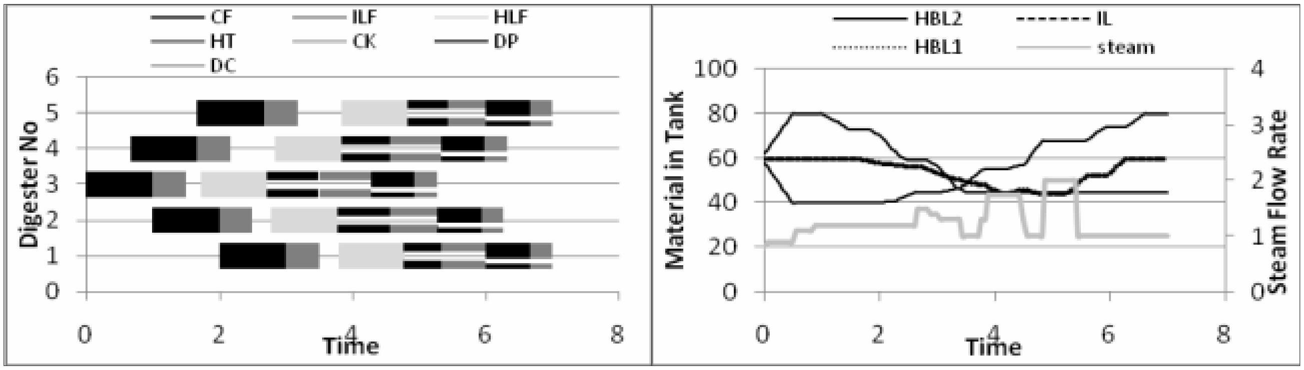


Fig. 1: Scheduling Optimization Results for Case 1 in Table 1

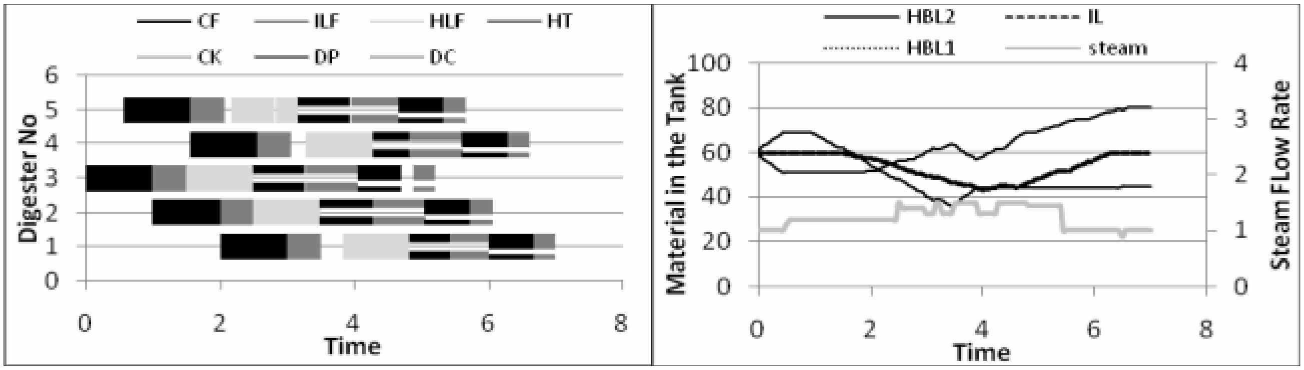


Fig. 2: Scheduling Optimization Results for Case 2 in Table 1

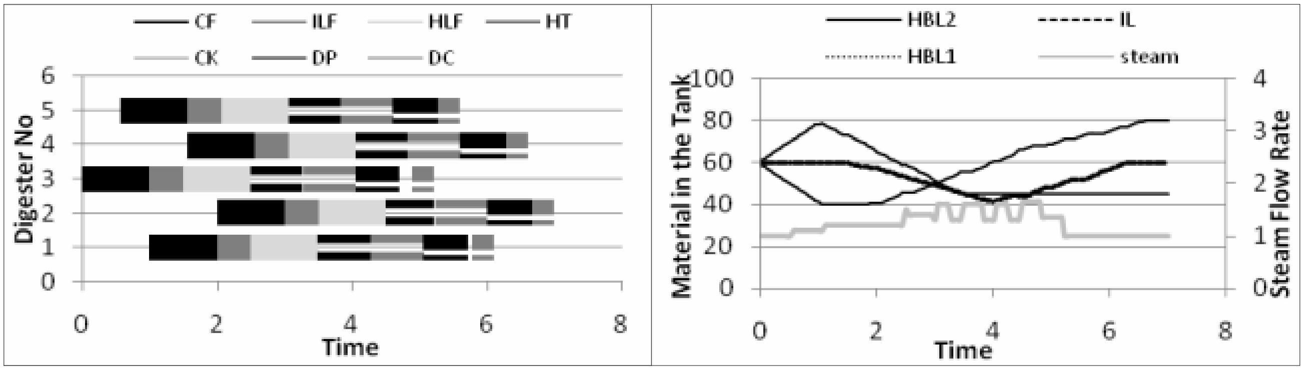


Fig. 3: Scheduling Optimization Results for Case 3 in Table 1

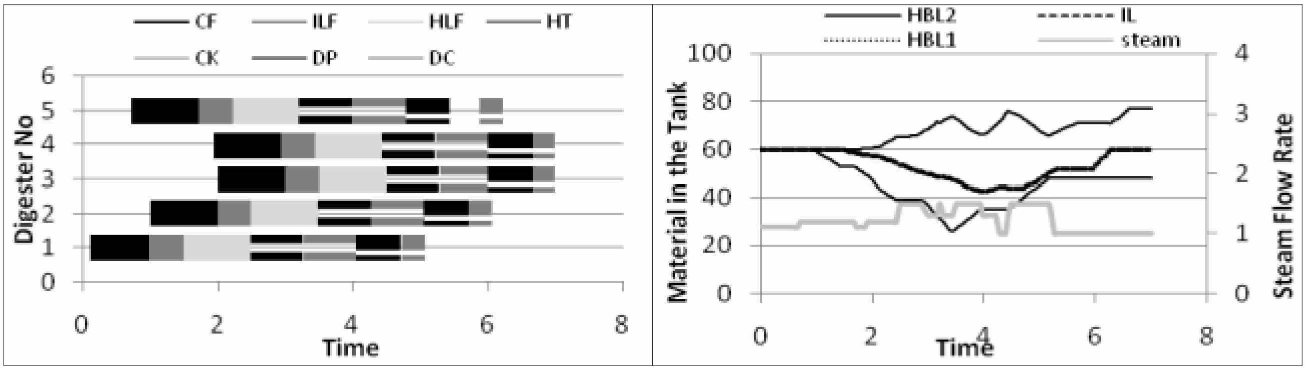


Fig. 4: Scheduling Optimization results for Case 4 in Table 1

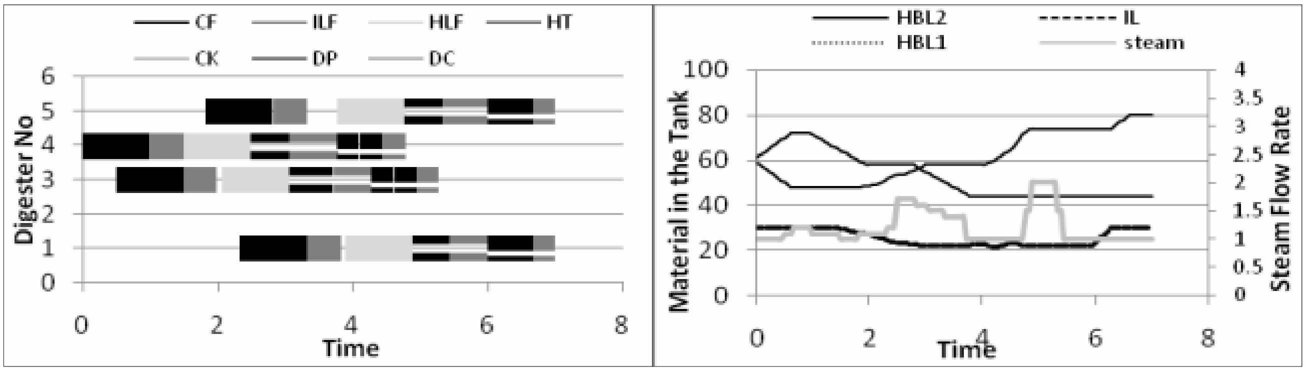


Fig. 5: Scheduling Optimization results for Case 5 in Table 1

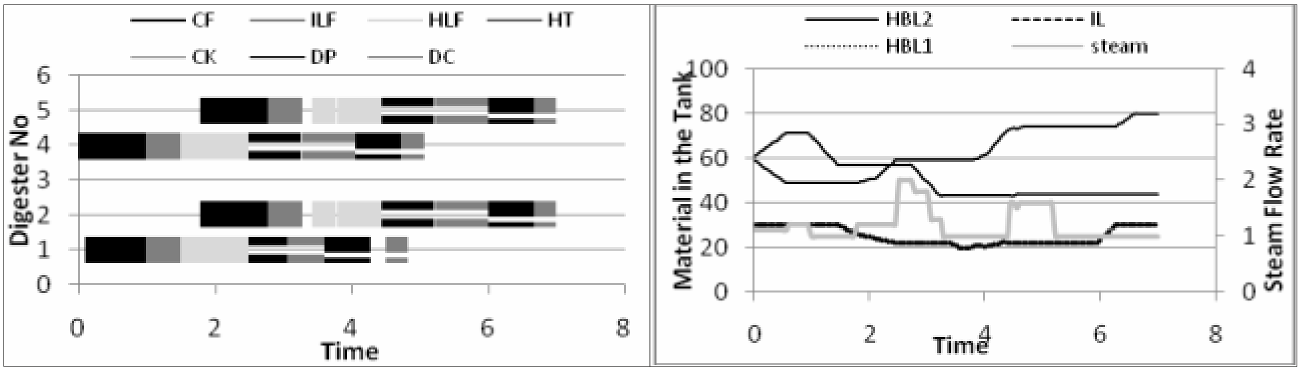


Fig. 6: Scheduling Optimization results for Case 6 in Table 1

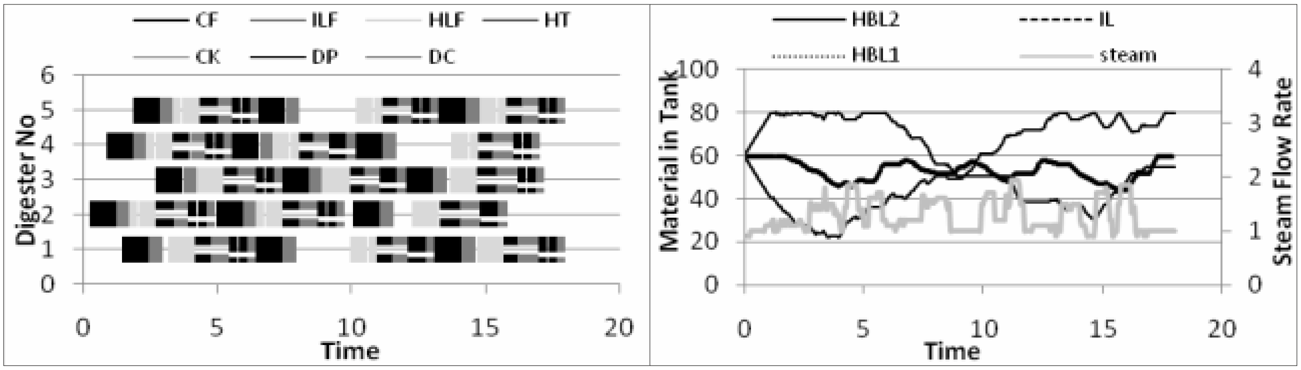


Fig. 7: Scheduling Optimization results for Case 7 in Table 1

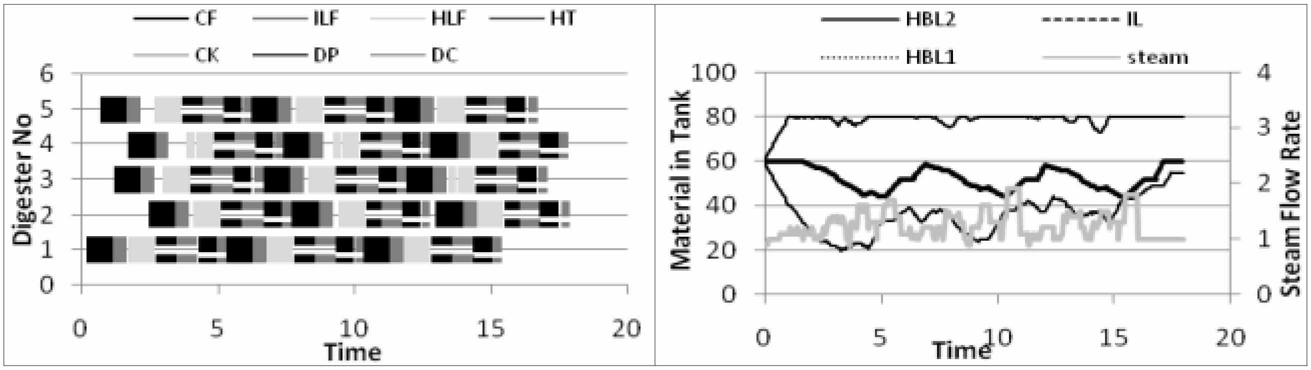


Fig. 8: Scheduling Optimization results for Case 8 in Table 1

digesters 1, 2 and 3 in line 1, as well as for digester 4 and 5 in line 2 there is no overlap of the CF, ILF, HLF, DP and DC phase. The levels in the various tanks are kept within the min/max limits (20-80) as is the case with the maximum steam flow rate (max limit - 2). Note that the idle time after ILF phase in all the digesters is utilized to align the HLF phases in the respective digesters in a line one after the other.

In Fig. 2, we simulate the schedule for a case 2 with the upper bound on steam decreased to 1.5. In this case, a different schedule is obtained while still respecting the modified constraints on the maximum steam flow and other shared resource constraints. It can be seen that heating tasks are now spread more evenly than in case 1 so as to have reduced total steam flow at any point of time. Also the idle times are realigned so as to avoid overlapping of the phases sharing common resources in the line. Also note that in this case, there is flow transfer occurring from HBL Tank 2 to Imp Liq Tank (while digesters 2 and 5 are in heating phase), thus, reducing steam consumption for heating WL. This causes the available steam to be used for having heating phase simultaneously in digesters 2 and 5 without violating the constraints on the maximum steam flow rate.

If we solve the same problem in case 1, for the objective of maximization of heating and cooking time (case 3), the schedule is obtained as shown in Fig. 3. In this case, it can be seen that idle time between phases is reduced considerably. There is 11.2 % increase in the heating and cooking time. For the problem in case 2, with the objective of maximization of heating and cooking (case 4), the results are shown in Fig. 4. In this case also, it can be seen that the idle time between the phases is reduced. There is 8.5 % increase in heating and cooking time as compared to case 2. In this case, it can be seen that the more steam requirement during the overlapping heating phases for digesters 2 and 5 as well as 3 and 4 are compensated by the flow transfer of the hot liquor from HBL Tank 2 to Imp Liq Tank during these times.

If we have a scenario (case 5) where initial amount of the HBL 1 is 30, Fig. 5 gives the schudule for the same. In this case, it can be seen that due to unavailability of HBL 1 (see the HBL 1 level almost touching the lower limit in Fig. 5) only 4 digester cycles are completed in the given time horizon. For the same problem, if we have maximization of heating and cooking time, Fig. 6 shows the optimal schedule. For this case, there is 19 % increase in the heating and cooking time as compared to case 5. The computational time for cases 1-6 is respectively, 4.2 s, 9.2 s and 5.1 s, 6.5 s, 17.3 s and 5.3 s respectively on a windows workstation with Intel Core Duo CPU 2 GHz with 1.96 GB of RAM using GAMS 23.6 version.

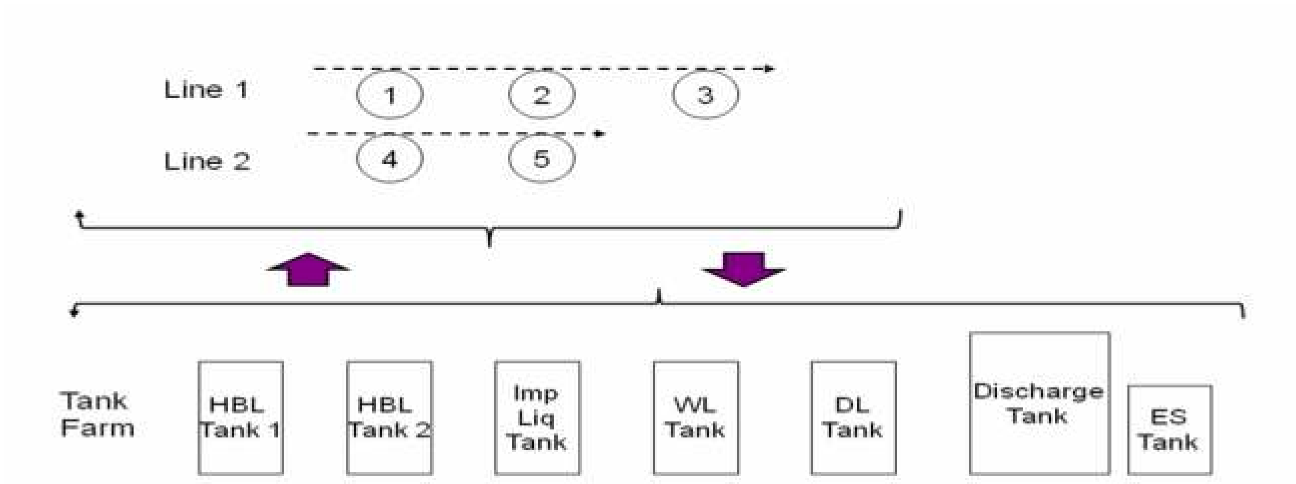
Now we simulate the scenario with bigger time horizon for maximization of production. In this case 7, the bounds on the levels are 20-80 and max steam flow rate is 2. The computational time is 1727 s. In this case, it can be seen that (see Fig. 7) all the constraints related to the shared resources and the levels in the tanks are satisfied. All digesters are producing three batches each in the given time horizon. For case 8, that involves the objective of maximization of heating and cooking time for the above problem, the results are shown in Fig. 8. The computational time required is 1028 s. In this case, it can be clearly seen that the idle time between various phases is reduced as compared to case 7. For this case, the increase in the total heating and cooking time is 20 % more than case 7.

Conclusions :

Based on the analysis of the results presented above, it can be concluded that the scheduling optimization can handle various scenarios related to different production targets and initial levels in the tanks for different time horizons. The formulation can address both the objectives of maximization of production as well as minimization of energy. It can be noted that the computational time depends on the size of the problem under consideration. However, the computational time can be reduced by taking process specific inputs in the formulation (not described here). Such analysis can be used to reduce the idle waiting times and plan other dependant activities in advance. This can also be used to analyze various what-if scenarios and help the operators take appropriate decisions to increase the productivity. Various additional constraints can be included in this formulation to suit specific operator needs. This formulation can also be easily extended to schedule productions of more than one quality. If there is some breakdown and deviation from the actual intended operation, the scheduling can be executed with the initial conditions at that point of time to get the optimal schedule corresponding to the changed scenario.

Problem Formulation :

A typical displacement batch digester involves various phases of operation such as 1. chip filling (CF), 2. impregnation liquor filling (ILF), 3. hot liquor filling (HLF), 4. heating (HT), 5. cooking (CK), 6. displacement (DS) and 7. discharge (DC). Typically in a line there are many digesters that share common resources such as chip filling conveyor, impregnation liquor pump, hot liquor pumps, displacement pumps, discharge pumps, blow line, etc. This implies that in a line any one



HBL tank 1: Hot black liquor (HBL1) from earlier batches (spent liquor); HBL tank 2: HBL2 from earlier batches (temperature is lower than HBL tank 1); Imp liq tank: Impregnation liquor (IL) (cooled liquor from HBL tank 2 + wash filtrates from washers); WL tank: Fresh white liquor (WL); DL tank: Displacement liquor (wash filtrates from washers); Discharge tank: Unbleached pulp; ES tank: Evaporation storage tank with spent liquor to be sent for evaporation.

Fig. 9: Schematic of digester house with displacement batch digesters

NOMENCLATURE:

Ăbbreviation	Description
CF	Chip Filling Phase
ILF	Impregnation Liquor Filling Phase
HLF	Hot Liquor Filling Phase
HT	Heating Phase
CK	Cooking Phase
DP	Displacement Phase
DC	Discharge Phase
HBL	Hot Black Liquor
HBL1	HBL from HBL Tank 1
HBL2	HBL from HBL Tank 2
IL	Impregnation Liquor
WL	White Liquor

digester can be in chip filing, impregnation liquor filling, etc., depending on the availability of the shared resources. In a digester house, many such lines can co-exist. All the digesters in the digester house also share the same set of liquor tanks to which the digesters keep adding liquor as well as taking out the liquor (depending on the phase in which digesters are in). Fig. 9 shows the schematic of a digester house having 5 digesters in 2 lines along with the details of the tanks (in tank farm) and the material contained in them.

In the scheduling problem under consideration, the digester is assumed to have seven phases in the sequential order as described above. The material consumed and produced during each phase is assumed to be known for each phase along with the duration of the phases. However, the duration of heating and cooking phase is assumed to be variable. This is done because, for cases that involve fixed production target, it is always desired to have maximum possible value of heating and cooking time to minimize energy. As per the operating constraints, digester can have wait phases after impregnation, displacement and discharge phase. There is also transfer of HBL2 from HBL tank 2 to Imp Liq tank. While this transfer happens, it exchanges heat with the WL. Steam is mainly required during heating phase as well as for heating WL.

The objective of the scheduling optimization problem, therefore, is to achieve the desired production targets for a given digester house while minimizing energy and satisfying the constraints in shared resources and bounds on levels in tank as well as steam availability. In order to formulate the scheduling optimization problem, state task network (STN) representation of digester phases is attempted. Each phase described above is considered as a task and the material consumed as well as produced by that phase is considered as the state.

Using the STN representation the scheduling optimization is formulated involving two different objectives: maximization of production and maximization of heating and cooking time. Both the objectives target minimization of idle time between phases to increase the productivity and minimize energy, respectively.

The formulation is attempted in

General Algebraic Modeling Systems (GAMS 23.6) framework and following constraints are considered using the standard discrete time formulation (Kondili *et al*., [4]; Shah *et al*., [5]):

1) Demand constraints: These constraints ensure that the demand for the pulp is satisfied at the end of the desired horizon.
2) Allocation constraints: These constraints ensure that the digester is occupied by only one task at any point of time for the duration of the task.
3) Capacity constraints: This ensures that the capacity of the digester during each phase is restricted between the minimum and maximum capacity possible.
4) Resource constraints: This ensures that the given resource is utilized at any time by only one of the digesters that qualifies to use that resource.
5) Material Balance Constraint: This constraint keeps track of the material going in and out of various tanks as well as digesters.

In addition to this, there are bounds related to the levels in each tanks. The durations of each task as well as suitability of each task in each digester is also used as an input.

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