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Heat Integration of Material Transfer Streams in Batch Processing Plants

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Batch processes are flexible allowing the production of different products within the same facility, and suitable for producing low volume, high value-added products such as pharmaceuticals and agrochemicals. The trend towards batch processing has necessitated the development of scheduling techniques. In addition to process scheduling, heat integration has been increasingly considered for batch plants to reduce external utility (e.g. steam and cooling water) requirements for tasks involving heating or cooling, such as endothermic and exothermic reactions. In this work, a mathematical technique for simultaneous process scheduling and heat integration of batch plants is presented. The formulation, based on a superstructure, aims to maximise the coincidence of availability of hot and cold process stream pairs with feasible temperature driving forces, whilst taking into account scheduling constraints. Heat integration during stream transfer can shorten the time required for heating and cooling in processing units, and is expected to enable higher production and lower utility consumption for batch plants. A case study is solved to demonstrate the application of the proposed mathematical model.

1. Introduction

Batch processes have gained considerable interest because of their flexibility and adaptability to produce different products using the same facility. Such processes are suited for producing low volume, high value-added products, which are commonly found in industries such as agrochemicals, pharmaceuticals, polymers, foodstuffs and fine/specialty chemicals. A common feature of the various batch processing plants is the use of fossil fuels as the primary energy source. Reliance on fossil energy in turn causes serious problems to the environment. Stricter environmental regulations due to increased public awareness towards and the need for sustainable development have urged the process industries to seek alternative renewable energy sources and efficient end use of energy. Improved energy utilisation can be achieved through enhancements in plant machinery and process integration. The literature review focuses upon process integration methodologies developed for energy recovery in batch processes. Although process integration has been successfully applied for energy conservation in continuous processes, different techniques are required for batch processes, where time is also an important constraint in addition to temperature. The complexity of the design and operation of batch plants has led to the development of various methods, tools and mathematical models for energy minimisation. In addition to batch processes, techniques of heat integration have also been developed for multiple plants/processes (Wang et al., 2013), locally-integrated energy sectors (Liew et al., 2013) and flexible operation (Abu Bakar et al., 2014).
While there have been many works addressing heat integration of batch plants, most of those only consider direct and/or indirect heat integration between processing units (Fernández et al., 2012). The opportunity for energy recovery through heat exchange between material streams during transfer was overlooked and remains to be exploited. This is the subject of the present study.

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2. Problem statement

The problem addressed in this paper can be briefly stated as follows. Given (i) production scheduling data, including equipment capacities, task durations, the time horizon of interest, the recipe for each product, raw material costs and product selling prices; (ii) operating temperatures for tasks, supply temperatures of raw materials and storage temperatures of final products; (iii) specific heat capacities of states and (iv) costs of external hot and cold utilities, it is desired to determine an optimal production schedule that maximises the profit, which is defined as the difference between product revenue and utility cost. The following assumptions are made for the problem:

- Constant heat capacities
- Negligible heat losses for temporary storage
- Counter-current heat exchangers

3. Model formulation

In this work, the mathematical modelling is based on the superstructure representations shown in Figure 1. It can be seen that each processing unit can receive material from and send material to other units or storage. The input material may be heated or cooled in the processing unit before the task starts in order to meet the operating temperature; similarly, the output material may be heated or cooled *in-situ* before leaving for further processing or storage. To reduce the use of external hot and cold utilities, heat exchange between output (i.e. intermediate and product) streams (Figure 1(a)) is considered, as well as heat exchange for raw material preheating (Figure 1(b)). Note that output streams are to have heat exchange before entering next processing units or storage, while raw material streams are, after leaving storage. If there are two or more states produced in a processing unit, they are assumed to leave the unit at the same temperature and treated as separate streams for heat integration. Also, it is currently assumed that external utilities can only be used in processing units through jackets; no utility heaters or coolers are available for use. In addition to the necessary scheduling constraints, the mathematical model consists mainly of mass and energy balance equations and heat integration constraints. To simplify process operation for practical considerations, the one-to-one heat integration arrangement is assumed, in which a hot stream can only have heat exchange with one cold stream.

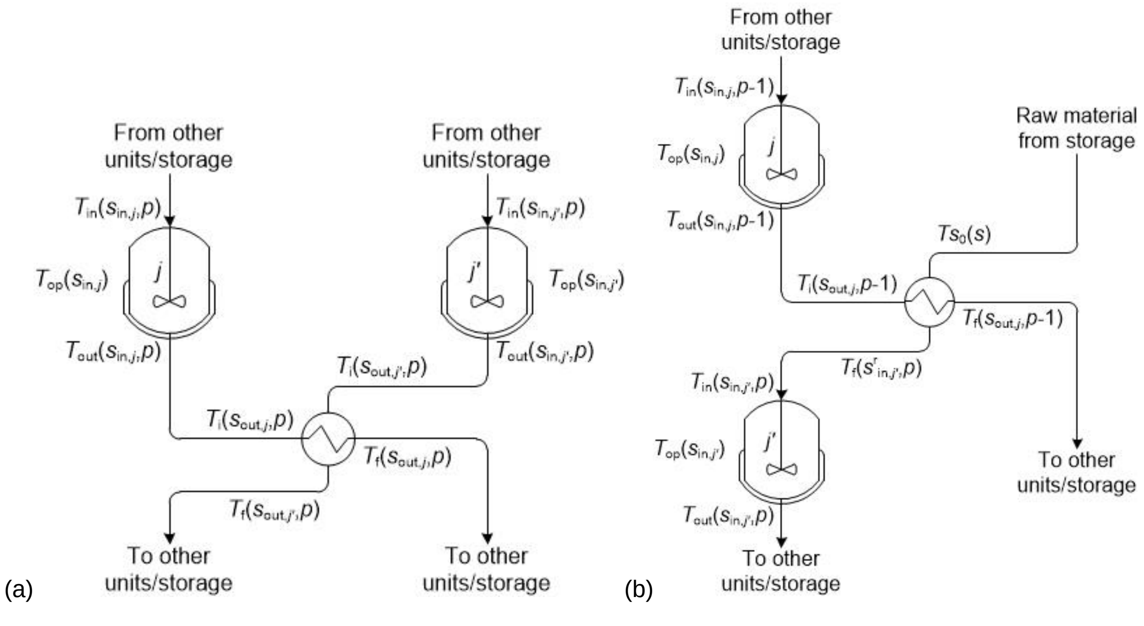

Figure 1: Superstructure for Heat Integration: (a) between outlet streams; (b) between outlet and raw material streams

For profit maximisation, the objective function may be defined as the difference between the product revenue and the costs of external hot and cold utilities (i.e. steam and cooling water).With the presence of bilinear terms (in energy balance equations) and the use of binary variables (mainly for process scheduling), the overall model is a mixed integer nonlinear programme (MINLP), for which global optimality cannot be guaranteed.

In the next section, the application of the proposed model is demonstrated through a modified literature case study. The model is implemented in the GAMS environment (Rosenthal, 2014) with BARON (Tawarmalani and Sahinidis, 2005) as the MINLP solver.

4. Illustrative case study

A multipurpose batch plant is to be scheduled to produce three products (S9-S11) from three raw materials (S1, S2 and S7) over a 16-h time horizon. The STN process representation is shown in Figure 2, where states S3-S6 and S8 are all intermediates. This case study is adapted from Pinto et al. (2008), with heating and cooling requirements for materials included to explore heat integration opportunities. Tables 1 and 2 present the pertinent data for the case study. For simplicity, it is assumed that each state has a dedicated storage vessel and each processing task is carried out in a dedicated reactor. Note that the supply temperature in Table 2 refers to the initial temperature of a state in the storage vessel. Therefore, the supply temperatures of intermediates and products are taken as zero.

Table 1: Processing data for the case study

Task	Unit	Duration (h)	Operating temperature (°C)	Capacity limit (kg)
1	R1	2	180	30-120
2	R2	2	40	20-80
3	R3	4	80	20-80
4	R4	2	120	50-200
5	R5	1	160	50-200
6	R6	1	100	35-140

Table 2: Material and utility data for the case study

State	Storage capacity (kg)	Initial inventory (kg)	Supply temperature (°C)	Product storage temperature (°C)	Heat capacity (kJ/kg °C)	Price ($/kg)
1	UL	AA	80	-	2.5	-
2	UL	AA	40	-	3.4	-
3	80	0	0	-	3.3	-
4	120	0	0	-	3.7	-
5	80	0	0	-	4.0	-
6	200	0	0	-	3.6	-
7	UL	AA	60	-	3.5	-
8	140	0	0	-	4.0	-
9	UL	0	0	40	3.2	10
10	UL	0	0	40	3.3	5
11	UL	0	0	80	3.7	10
Material transfer time					10 min	
Minimum temperature difference					10 °C	
Cooling water cost					$ 0.6/MJ	
Cooling water inlet/outlet temperature					20/30 °C	
Heat capacity of cooling water					4.2 kJ/kg °C	
Mass flow rate of cooling water					1,800 kg/h	
Steam cost					$ 3/MJ	
Saturated steam temperature					200 °C	
Latent heat of steam					1,940 kJ/kg	
Mass flow rate of steam					40 kg/h	

It can be seen in Figure 2 that unit R1 is to have heating for its input S1 and cooling for its output S4, as the supply temperature of S1 is lower than the operating temperature of R1, and the latter is higher than the operating temperature of R4. Similarly, the potential heating requirements for the inputs of R3 and R5 and the outputs of R2-R4 can be identified from Figure 2, as well as the potential cooling requirements for the outputs of R5 and R6. However, uncertainties remain for R4 and R6. The input of R4 consists of S4 and S5, which are produced at different temperatures and can give a mixture temperature higher or lower than its operating temperature. In the case of R6, if the product storage temperature of S11 (80 °C) is achieved by utility cooling in R5, then S8 will leave R5 at 80 °C, which is lower than the operating temperature of R6 (100 °C). However, if the product cooling is achieved by heat exchange, the final temperature of S8 can be higher than the operating temperature of R6.

The hot and cold streams for heat exchange can also be identified from Figure 2. There are three potential hot streams (S4outR1, S8outR5 and S11outR5) and five potential cold streams (S1inR1, S3outR2, S5outR3, S6outR4 and S7inR5). Note that the feed stream of R2 (S2inR2) and the product streams of R6 (S9outR6 and S10outR6) are not included: the former has no need for heating or cooling, while the storage temperatures of the latter can only be achieved with cooling water. Assuming the batch size to be fixed at the maximum, the objective in this case study is to maximise the profit given by the difference between product revenue and utility cost.

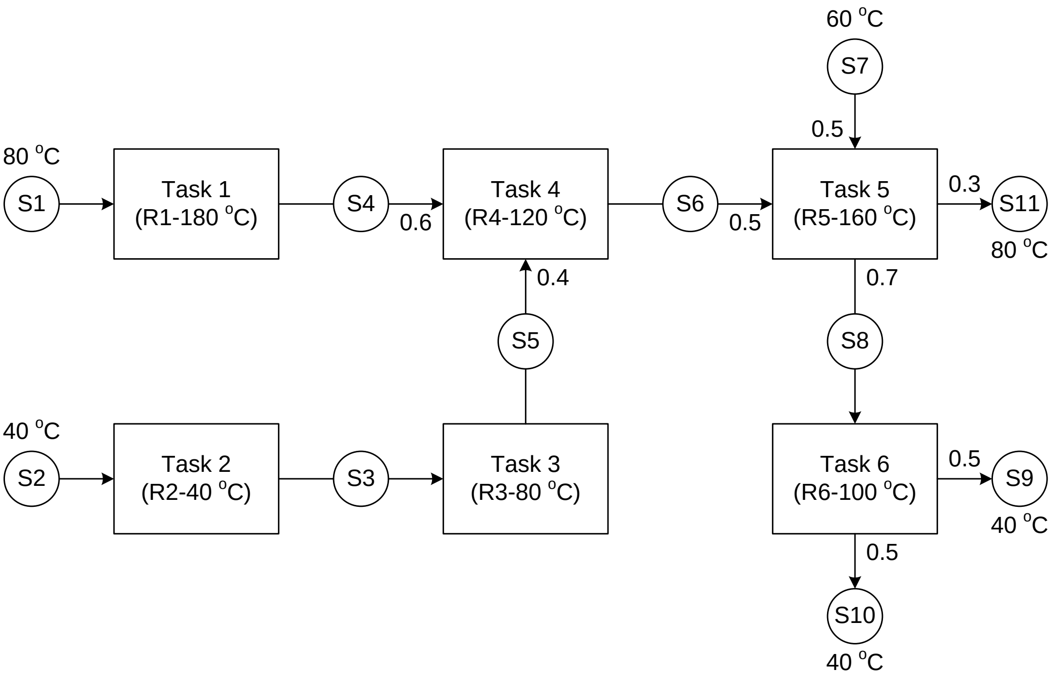

Figure 2: STN representation for the case study

Batch operation is often carried out with fixed batch size in the process industries to minimise changes. In this case study, the batch sizes for all processing units are fixed at the maximum capacities given in Table 1. Prior to the exploration of heat integration opportunities, the batch plant produces 140 kg of S9, 140 kg of S10 and 120 kg of S11 within the 16-h time horizon, while consuming 161.76 MJ of steam and 193.56 MJ of cooling water. This gives a profit of $ 2,698.58, obtained from the proposed model by setting all the binary variables associated with heat exchange to zero. Figure 3 shows the Gantt chart for the case without heat integration. Note that the heating and cooling required in R5 increase the material residence time to at least 2.47 h, which is much longer than the task duration of 1 h. Thus, there is not enough time to process another full-size batch in R5.

When heat exchange between process streams (three hot, S4outR1, S8outR5 and S11outR5; five cold, S1inR1, S3outR2, S5outR3, S6outR4 and S7inR5) is considered, the plant is able to produce 140 kg of S9, 140 kg of S10 and one batch more of S11 (i.e. 180 kg) within the same time horizon. The utility cost can be reduced to $ 479.74, giving a profit of $ 3,420.26. This corresponds to a 26.7 % improvement compared to the case without heat integration. Figure 4 shows the optimal schedule with heat exchange between process streams. An overall comparison shows that heat integration of material transfer streams enables the batch plant to produce a larger quantity of products with much less consumption of external utilities.

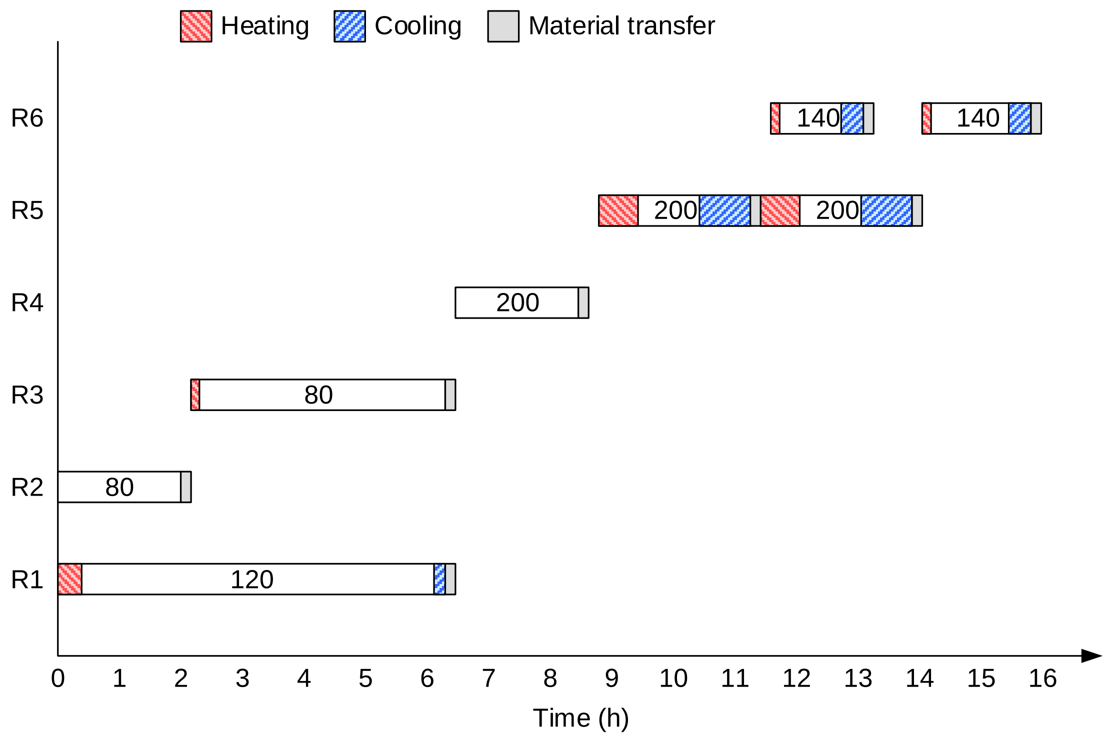

Figure 3: Gantt chart for the case without heat integration

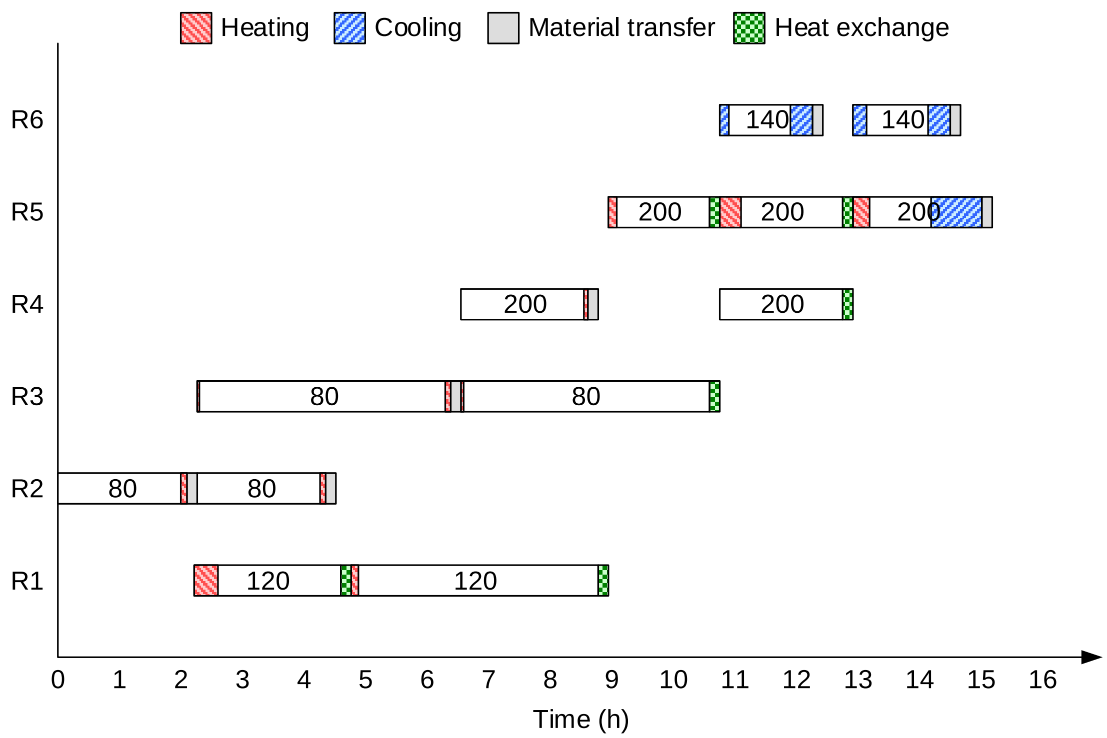

Figure 4: Optimal schedule with heat exchange among raw material and output streams

5. Conclusion

Based on a robust scheduling framework adapted from Seid and Majozi (2012), a superstructure-based mathematical model for simultaneous process scheduling and heat integration of batch plants has been developed in this paper. The formulation ensures proper sequencing of tasks over a given time horizon, with the aim of synchronising the material transfer times so as to maximise heat recovery. An illustrative case study was solved to demonstrate the application of the proposed model. The results show the twofold benefit from heat integration of process streams: the need for external hot and cold utilities, as well as the dedicated times for heating and cooling within processing units, can be eliminated with positive cost implications (a 20 % utility cost saving). Furthermore, more batches of product can be produced hence increased profit (an almost 20 % profit increase) with the elimination of dedicated in-unit heating and cooling times. It should be noted that, in the current study, external utilities are only allowed to be used in processing units. This could render utility heating and cooling prior to heat exchange and, consequently, reduce the driving force and potential for heat recovery. In future work, the use of utility heaters and coolers for material transfer streams will be taken into account. Direct and indirect heat integration between processing units may also be considered to provide further energy recovery opportunities.

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