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Petri Net Methodology for Optimisation of Heat Integration and Batch Process Scheduling

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In this work, a Petri net (PN) based methodology for incorporating heat integration in batch process scheduling was presented. With this method, heat integration and batch process scheduling can be optimised simultaneously. Scheduling model, firstly, was modified and constructed by PN. The disadvantages of timed Petri net (TPN), such as the asyntactic expression and unenforceable concurrent, were overcome availably and scheduling optimization can be achieved easily. Secondly, based on the similarity of PN and time-dependent heat cascade analysis technique (TDHCA) in carrying out discrete problem, PN for TDHCA was modelled. Using this model, the step to make sure streams distribution in temperature intervals was avoided and the calculation of heat deficiency was simplified. Finally, with the facility of multi-view integrated modelling, PN models for scheduling and heat integration problems were fused together. The problems for incorporating scheduling in batch process heat integration were simultaneously optimised by the combined model. An illustrative example was presented to demonstrate the validity and advantages of the proposed approach.

1. Introduction

Recently, heat integration has been introduced to batch processes. In the early phase, rescheduling was applied to optimise heat integration of batch processes, however, it could result in a flagrant potential ---- increasing the make-span (Kemp, 2007). Since optimal scheduling is exceedingly crucial in batch processes (Halim and Srinivasan, 2009), many researchers have put their attention to incorporating heat integration in batch process scheduling. Nevertheless, most of their work were based on MILP (Seid and Majozi, 2014) or MINLP formulations (Lee et al., 2015), when heat integration and scheduling are considered together, the solutions become far more complicated.
The well-known and widely used Pinch Design Method in the heat integration is a potential method to avoid complex calculations in mathematics programming methods. Pinch Technique is a simple and easy approach of optimisation based on thermodynamics rules (Ebrahim and Kawari, 2000). The optimum energy needed and enthalpy interval of heat transfer matched were obtained by using clear Composite Curves (Xiao et al., 2006), and the heat cascade can be calculated by the Problem Table Algorithm (Wan Alwi et al., 2013). Pinch Technology has been widely applied in design (Wang et al., 2014) and modification (Chew et al., 2014) of the Total Site Heat Integration process.
Petri net (PN) is a promising technique to solve many scheduling problems (Başak and Albayrak, 2015), Emergency plans (Hamzi et al., 2013) and Heat Integration (Jia et al., 2010). In 1974, time factor was imported into PN by Merzin to manage system time availably, since then, several pattern time or timed Petri net (TPN) have been developed, such as P-TPN, T-TPN, Timing-constraint PN and TCPN (Jamro et al., 2015). Using those TPN, scheduling problems can be optimised intuitively. Compared with other methods, the structure of PN method used to formulate a scheduling problem is clear and brief; a limited structure can represent infinite batches (Wang et al., 2014). Logic can be express simply and effectively

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(Chen et al., 2010). An approach based on the TPN for incorporating water integration in batch process scheduling has been presented (Li et al., 2012).
Considering above advantages, a PN method to synthesize heat integration and scheduling problems is proposed in this paper. This study is organized as follows. In Section 2, a modified PN of scheduling problems is proposed, instead of asyntactic TPN. In Section 3, time-dependent heat cascade analysis technique (TDHCA) (Kemp and Deakin, 1989) based on the Problem Table Algorithm of Pinch Technology (Wan Alwi et al., 2013) is formulated by PN. In Section 4, PN models for scheduling and heat integration are composited together to simultaneously optimise a problem for incorporating scheduling in batch process heat integration.

2. PN for optimum-scheduling problem

A TPN for sub-operation of scheduling problem is shown as Figure 1. Where OP is the place of operation; P′ is the place of raw material; P″ is the place of product; RP is the place of equipment; T_S is the transition of starting operation; T_E is the transition of ending operation; t_{op} is the duration of operation; dot located in P′ is the mark of raw material waiting for operation; dot located in RP explains the equipment is idle. Constructing and compositing all raw material, operation and equipment, a TPN for scheduling problem is complete.

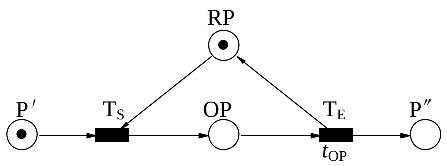

Figure 1: TPN for sub-operation

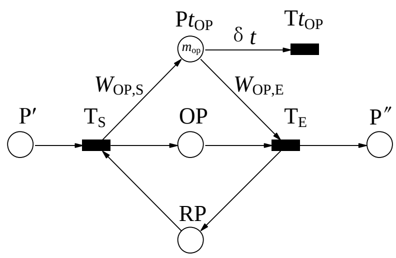

Figure 2: Modified PN for sub-operation

Several shortages, however, such as asyntactic expression time factors, unenforceable concurrent and conflict and unreachable analysis, are existing in the above TPN model. So, the above model can be modified by self-adaptive weight and marks if time factors are treated as a set of PN elements.
To characterize the states of operations in this system, it is necessary to make sure the preparation of raw material before the operation and also equipments and the location of material. Five places and three weights are thus adopted to represent these variables. The modified PN for sub-operation is present in Figure 2, where m_{OP} is the mark of time remaining in the operation; P_{tOP} is the place of operation duration; T_{tOP} is the transition of operation duration; $W_{OP,S}$ is the weight of starting operation, the value is t_{OP}+ε and ε is a small positive; $W_{OP,E}$ is the weight of ending operation, the value is $ß \times m_{OP}$-ε and $ß$ is a value greater than 1; δ_t is a unit of time.
Using the PN, the function of the TPN can be fulfilled, in the meantime, the drawbacks of TPN can be avoided, system reachability and time performance can be acquired easily by graphical and mathematical tools, or the state equation, either one.

3. PN for heat integration

TDHCA diverted from continuous Pinch analysis is a popular heat integration technique for batch process. In this method, temperature and time were divided into temperature intervals and time intervals. The individual process streams are located in their respective time intervals, the boundary of the time intervals is set based on the start and end time of the process streams.
To depict the division of temperature and time intervals, three places and two weights are employed to express the relationship between time intervals and streams and also the streams and temperature intervals. The PN for time cascade analysis (Figure 3) and the PN for heat cascade analysis (Figure 4) were built.

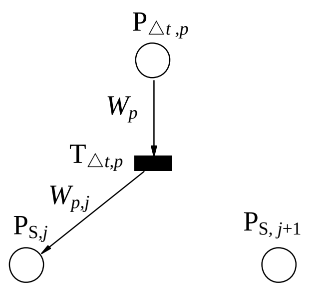

Figure 3: PN for time cascade analysis

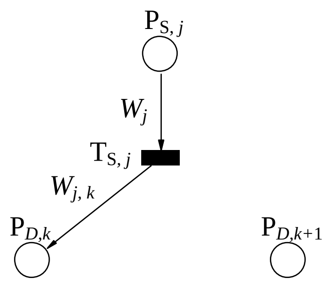

Figure 4: PN for heat cascade analysis

In Figure 3, $P_{\Delta t,p}$ is the place of time interval p; $P_{S,j}$ and $P_{S,j+1}$ are the places of stream j and j+1, if stream j is located in p, an arc from transition $T_{\Delta t,p}$ to place $P_{S,j}$ is arranged, if not, no arc can be found between them; the value of weight W_p is equal to $m(P_{\Delta t,p})$ and $m(P_{\Delta t,p})$ is the marks of $P_{\Delta t,p}$; the value of weight $W_{p,j}=CPS_j \times m(P_{\Delta t,p})$, CPS_j is the heat-capacity flow rate of stream j. And in Figure 4, $P_{D,k}$ is the place of temperature interval k, if interval k is involved in stream j, an arc from transition $T_{s,j}$ to place $P_{D,k}$ is arranged, otherwise no arc; weight $W_j=m(P_{S,j})$ and $m(P_{S,j})$ is the mark of $P_{S,j}$; weight $W_{j,k}=\Delta T_k \times m(P_{S,j})$ and ΔT_k is the temperature difference of temperature interval k.
By means of place $P_{S,j}$ fusion, communication between these two nets can be modelled. Consequently, the whole PN for batch process heat integration can be constructed. Pinch Point of the respective time intervals and external utility requirement can be determined by firing this PN.

4. PN for incorporating Pinch analysis in batch process scheduling

In a batch process, the duration of an operation is contained in process time, empty time, cleaning time and duration of material movements. To simplify modelling, in the work, heat exchange engage in the entire operation duration, it means that the periods of stream are equal to operation duration.
According to this assumption, place Pt_{OP} and $P_{\Delta t,p}$ can be fused, transition Tt_{OP} and $T_{\Delta t,p}$ can also be fused, then the PN models for sub-operation and heat integration are combined together. But some places and transitions are redundant, in the sense that their removal does not change the behaviour of the original model. In this combined PN, $P_{S,j}$ and $T_{s,j}$ are needless, it is possible to eliminate them. Then, the reduced PN for incorporating Pinch analysis in batch process scheduling is as shown in Figure 5.

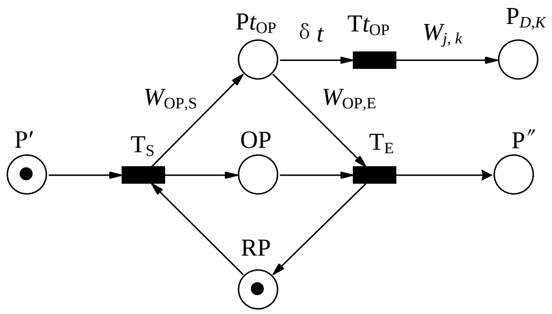

Figure 5: PN for incorporating Pinch analysis in batch process scheduling

Specifically, step size δ_t is set to schedule the start and end time, so the PN based method is discrete.

5. Case study

In this section, the above model is applied to a hypothetical batch process shown in Figure 6. The parameters for the heat streams are given in Table 1. The minimum temperature difference ΔT_{min} is equal to 10 K.

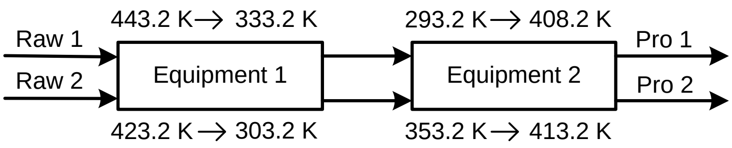

Figure 6: Recipe for this example

Table 1: Streams data for this example

Operation	ID	Initial Temperature (K)	Final Temperature (K)	heat-capacity ($kW\cdot K^{-1}$)	Duration (h)
OP1,1	H1	443.2	333.2	4.00	5
OP1,2	C2	293.2	408.2	-5.00	5
OP2,1	H3	423.2	303.2	10.00	8
OP2,2	C4	353.2	413.2	-6.00	5

*Where $OP_{2,1}$ means raw material 2 is operated in equipment 1.

Two batches PN models for incorporating Pinch analysis in batch process scheduling are represented in Figure 7. Two dots located in P′ indicate two batches and IP are the place of interval product.

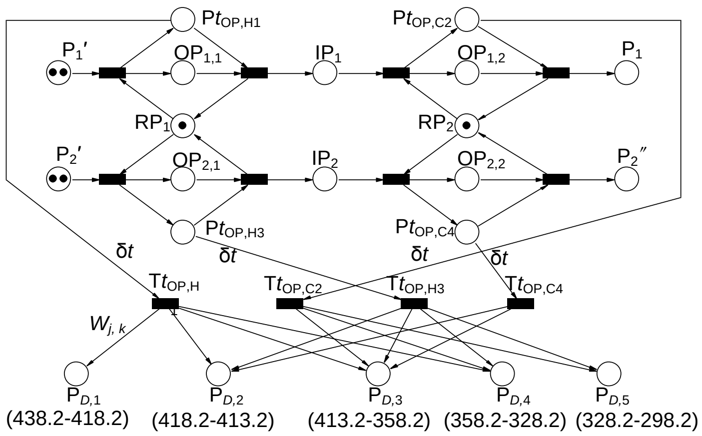

Figure 7: PN for incorporating Pinch Analysis in scheduling of two batches

Table 2: External utility requirement for the example

ID	external utility /kWh	Make-span /h
1	20,000	31
2	18,250	31
3	20,800	31
4	22,550	31
5	32,950	46

Table 2 is the different schedules for external utility requirement and Make-span. The best project is ID 2. Sequence of the firing transitions is listed as follows:

$T_{S1,1}T_{E1,1}T_{S1,2}T_{S2,1}T_{E1,2}T_{E2,1}T_{S1,1}T_{S2,2}T_{E1,1}T_{E2,2}T_{S1,2}T_{S2,1}T_{E1,2}T_{E2,1}T_{S2,2}T_{E2,2}$;

Corresponding sequence of operation:

$OP_{1,1}\rightarrow OP_{1,2}$/ $OP_{2,1}\rightarrow OP_{1,1}$/ $OP_{2,2}\rightarrow OP_{1,2}$/ $OP_{2,1}\rightarrow OP_{2,2}$

Where "→" means next operation, "/ " means simultaneous operation.

The Gantt chart for the heat-integrated schedule is shown in Figure 8. The arrows mean that heat integration can occur between the linked two operations.

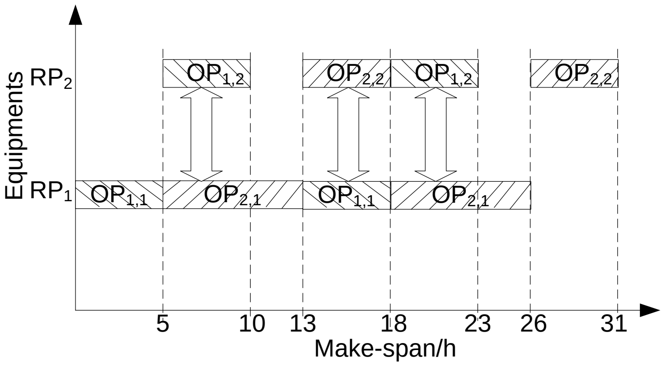

Figure 8: Gantt chart for the example

Two heat exchangers (1, 2), two coolers (C1, C2) and one heater (H1) are needed for heat integration and heat recovery is 14,700 kWh, the heat exchanger network (HEN) is as shown in Figure 9, where H1,2 means hot stream H1 located in second batch, the others is same as it.

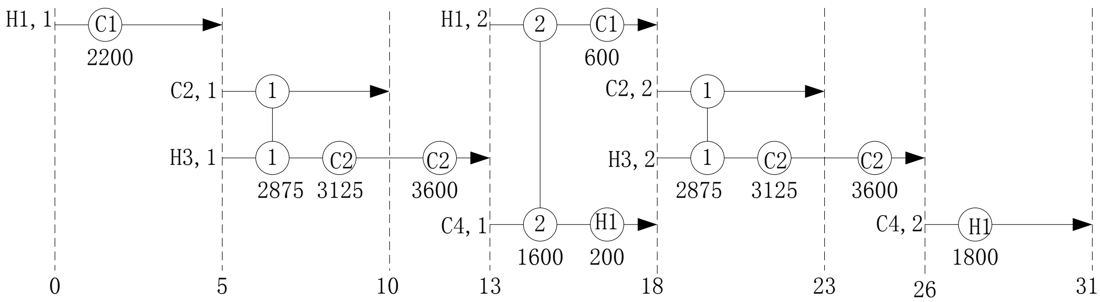

Figure 9: HEN for the example

6. Conclusions

In this paper, a method based on PN for incorporating heat integration in batch process scheduling is developed. Compared with MILP or MINLP, the modelling process of PN for scheduling problems is more visualized and simple. Based on the similarity of discrete problem between TDHCA and PN, TDHCA technique is modeled by PN and combined with PN for scheduling to simultaneously optimise a problem of incorporating scheduling in batch process heat integration. Application of the method to a hypothetical example shows how utility requirement can be reduced considerably with optimum make-span.

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