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A Colored Petri Net Model for Analyzing Batch Sequential Control System

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Abstract: This paper describes a modeling and analyzing method for batch sequential control systems by using colored Petri net (CPN) model. For this purpose, we propose systematic procedures to create CPN model from a various information based on ISA S88, i.e., master recipe, equipment information and batch schedule. To examine the effectiveness of the proposed method, we applied it to a two-step polymer process as an example. Through the numerical experiment, it is shown that we can provide an environment to simulate batch sequential control systems easily, and to find out certain conflicts of operation in the process.

Keywords: Batch Process, Sequential Control, Discrete Event System, Colored Petri Net (CPN), S88.01.

1. Introduction

Recently, to satisfy highly diversified customer needs, chemical plants have been faced to various paradigm shifts in manufacturing. For example, a shift from the mass production to the multi-item, small-lot-sized production has been considered in many chemical processes. Under such circumstances, we believe batch technology will become a key element in the coming age.

Generally speaking, batch sequences representing actual procedures for plant operations are to be generated by using various information, e.g., plant facility/equipment information, production schedule and production recipe. In addition, it is very popular in such process that certain units/resources are shared commonly among different batches. It is highly desired, therefore, to analyze the operation of the created batch sequences so that serious deadlocks and/or conflicts will not occur in real processes.

With this point of view, in this study, we concerned with a modeling and analyzing method by using colored Petri net (CPN) (Jensen, 1996) for batch sequential control. While standard Petri net (PN) has only one type of token, CPN contains several types distinguished by colors. Due to this characteristic, we can model the batch sequence very simply by expressing different status regarding share of common resources in different color. To examine the effectiveness of the proposed method, we applied it to a two-step polymer process as an example.

2. Batch process model

Let us suppose that model of batch process is described based on S88.01 (ISA, 1995). Moreover, we assume that necessary information such like PFD (Process Flow Diagram), equipment information, master recipe, unit procedure in the form of SFC (Sequential Function Chart) and batch schedule are given for the batch sequence.

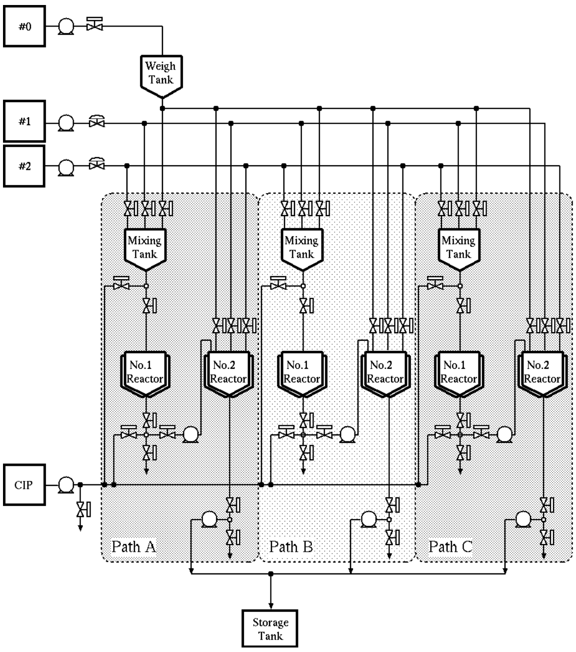

Fig. 1 Two-step polymer process

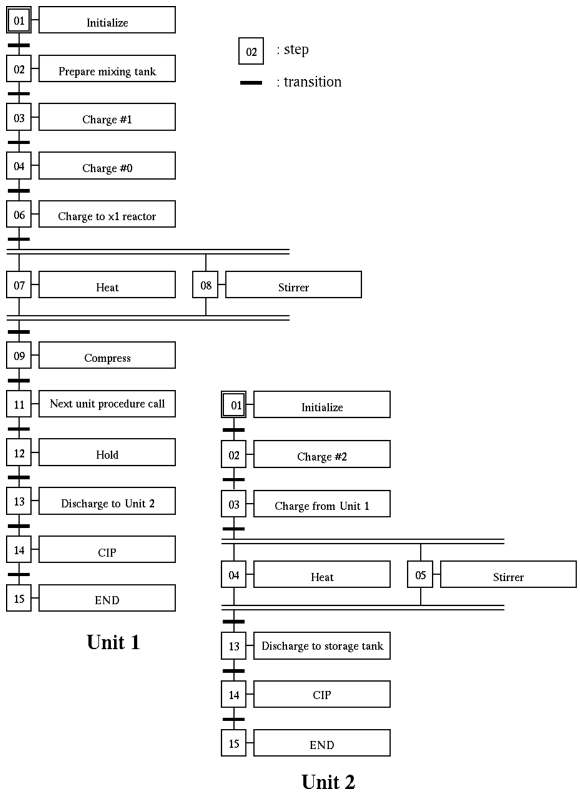

Fig. 2 Unit procedures for the example process

Below, we will explain about our procedure using the process chosen as the case study. Figure 1 shows such a process with three paths (Path A, B and C), each of which includes following two batch units:

- Unit 1: No. 1 reactor and mixing tank,
- Unit 2: No. 2 reactor.

Material storage tanks (#0, #1 and #2), weigh-tank, CIP and storage tank are considered as common resources and shared among the paths. Figure 2 shows the unit procedures for this process.

3. Modeling and analyzing procedure

As a modeling tool, we employed PN since batch sequences can be expressed as the discrete-event system (DES), and PN have been widely applied to model, control and analyze dynamic behaviors of DES due to the easiness of the graphical and mathematical representation. However, we need to deal with the enormous numbers of status in actual plants. Hence, we especially focused on CPN known as a high-level net of PN. In CPN model, we can represent DES more compactly by color attribute. Its mathematical expression and also hierarchical structure are suitable to analyze the actual system and discover conflicts. The conflicts result from two or more procedures that will compete for the same resources at same time.

The proposed procedures to model the batch sequence and to discover certain conflicts are summarized as follows:

1) Convert SFC into the standard PN without taking the sharing of common resources into account.
2) By using equipment information and batch schedule, convert the above standard PN into CPN while assigning common resources at

each operation.

3) Derive a modified net to satisfy the physical constraints on capacity and/or unit number. (Hereinafter, we call it controlled net.) For this purpose, the algebraic method known as the Moody's is applied.
4) Discover conflicts both by structural analysis and simulation of the controlled CPN.

The detail of each step is explained in the following.

3.1 Convert SFC into standard PN

At first step, we must obtain the incidence matrix of SFC from the given unit procedure to generate a standard PN for the sequence. The ***i-j*** element of the incidence matrix, a_{ij} indicates the relation between step and transition (refer to Fig. 2).

$$a_{ij} = \begin{cases} 1 & \text{if an arc from step } i \text{ to transition } j \text{ exists} \\ -1 & \text{if an arc from transition } j \text{ to step } i \text{ exists} \\ 0 & \text{otherwise} \end{cases}$$

The incidence matrix for Unit 2 in Fig. 2 is described as follows:

$$\boldsymbol{D}_{SFC2} = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Considering the “step” in SFC as the “place” in PN, we can get the incidence matrices of standard PNs straightforwardly.

In some cases, however, a certain unit procedure needs synchronize with the others. To realize the synchronization, we combine thus derived multiple PNs by appropriate algebraic transformations based on the information regarding unit procedure. The synchronized PN for the example process is shown in Fig. 3.

3.2. Convert standard PN into CPN

The information required for converting of standard PN into CPN is as follows:

- Master Recipe
  Formula, Equipment Requirements,
  Unit Procedure
- Equipment Information
- Batch Schedule

Using this information, we can create CPN model as follows:

a) Add color attributes to the places

a-1 Select a place corresponding to the initial step in SFC.

a-2 Relate a necessary batch unit to the above place from equipment requirements and equipment information.

a-3 Add a color attribute, which indicates the batch unit related at a-2, to the place.

a-4 If the current place is the last one, go to b). Otherwise, select a next place and return to a-2.

b) Add color attributes to the transitions

b-1 Select a transition corresponding to the initial step in SFC.

b-2 Add the color attributes as same as the input place.

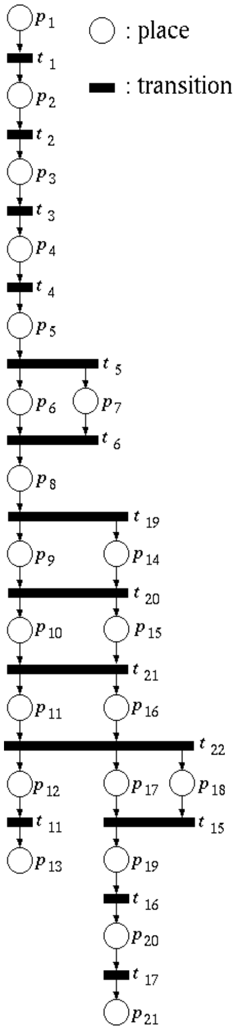

Fig.3 Sequence model by standard PN

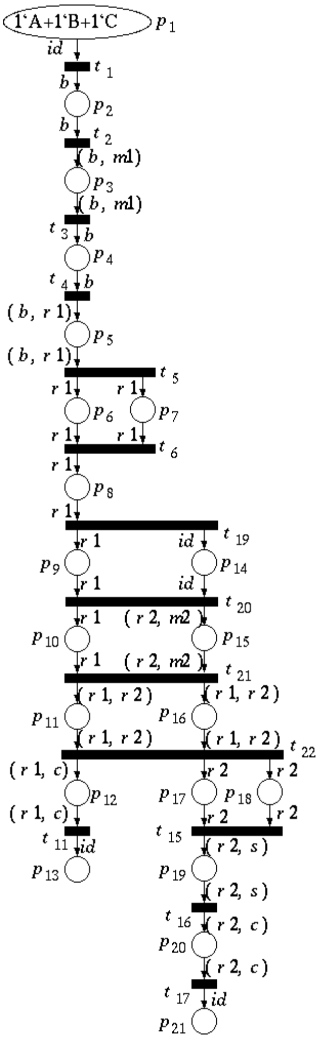

Fig. 4 Sequence model by CPN

b-3 Select a transition coming from the output place, and then return to b-2. If there is no transition, go to c).

c) Add color functions to arcs

By using equipment information and batch schedule, add proper color functions to arcs to define the batch unit corresponding to the operation of output place or transition.

The obtained CPN model by the above procedures is shown in Fig. 4.

3.3 Derive sequential control system

Additionally, thus obtained CPN model must satisfy the constraints on capacity and/or unit number. To derive the controlled net, we apply the algebraic method known as the Moody's (Moody, *et al.*, 1998).

Consider the constraints described as follows:

$$\boldsymbol{L}\mu_{\boldsymbol{p}} \le \boldsymbol{b} \qquad (2)$$

where μ_p is the marking vector of the process net. Let n_c being the number of constraints, n the number of places, $\boldsymbol{L}$ denotes the coefficient matrix ($\in Z^{n_c \times n}$). Moreover, $\boldsymbol{b}$ is the coefficient vector ($\in Z^{n_c}$). Then, we can calculate an incidence matrix of PN controller, $\boldsymbol{D_c}$ and the initial marking μ_c as follows:

$$\boldsymbol{D_c} = -\boldsymbol{L}\boldsymbol{D_p} \qquad (3)$$

$$\mu_{\boldsymbol{c}} = \boldsymbol{b} - \boldsymbol{L}\mu_{\boldsymbol{p}} \qquad (4)$$

where $\boldsymbol{D_p}$ is the incidence matrix of the process net.

Now, we are ready to describe the PN controller based on the above incidence matrix. Finally, like c) in subsection 3.2, adding color functions to arcs of the PN controller, we can get the batch sequential control system modeled by CPN. Figure 5 shows a sequential control system of Fig. 4.

3.4 Conflict analysis

In order to find the conflicts in the batch sequential control system, we applied the following two analysis methods.

• Structural analysis of CPN

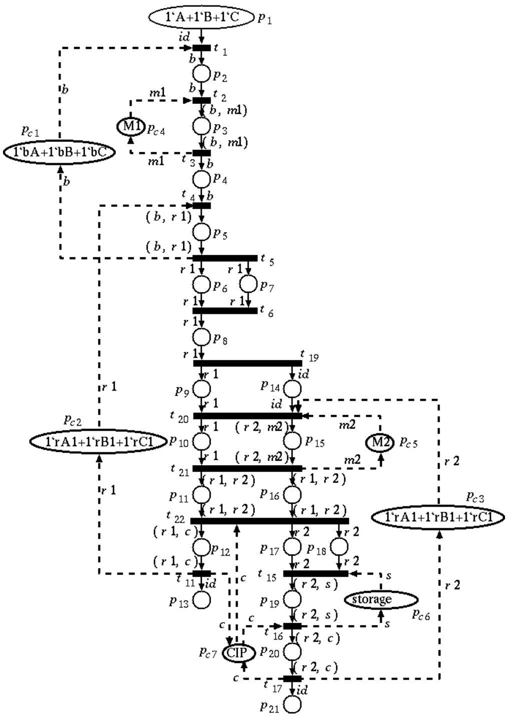

Fig. 5 Batch sequential control system model

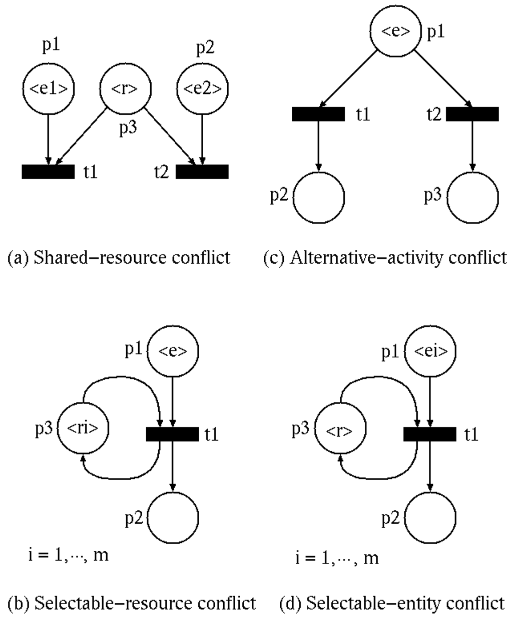

Fig. 6 Classification of structural conflicts

• Simulation

Structural conflicts in CPN model are classified into four types as shown in Fig. 6 (Lin, *et al.*, 1997). Shared-resource conflicts (a) occur when a resource (p3) is shared by two or more procedures at same time. Selectable-resource conflicts (b) denote that a procedure has several available resources (i.e. <ri>, i = 1, …, m) at any time. Alternative-activity conflicts (c) denote that an entity in a place (p1) has two or more enabled transitions at same time (i.e. t1 and t2). Selectable-entity conflicts (d) denote that several entities in a place (i.e. <ei> in p1, i = 1, …, n) compete for the same resources (i.e. <r> in p3). Based on the examination according to the above classification, conflicts can be analyzed directly from the structure of CPN model.

However, even if a certain part of the CPN model would matches structurally with the any conflict types mentioned in the above, it does not necessarily mean conflicts occur actually from the initial status of the process. Through simulation, we can verify if such conflicts will actually occur at the points predicted by the structural analysis. In this study, using Design/CPN (http://www.daimi.au.dk/ design CPN/), we carried out simulation based on the following two methods.

1. Fire any enabled transitions one by one, and check whether conflicts will be occurred at each firing.
2. By using a report function of Design/CPN, check the maximum number of enabled tokens at each place. If the number of the foregoing tokens is more than that at a certain place, there exists conflict.

In the second case, to avoid the conflicts, we must decide priorities of firing among the tokens so that the condition on the maximum number will be satisfied. (In this study, the priorities are randomly determined by the simulator.)

4. Case study

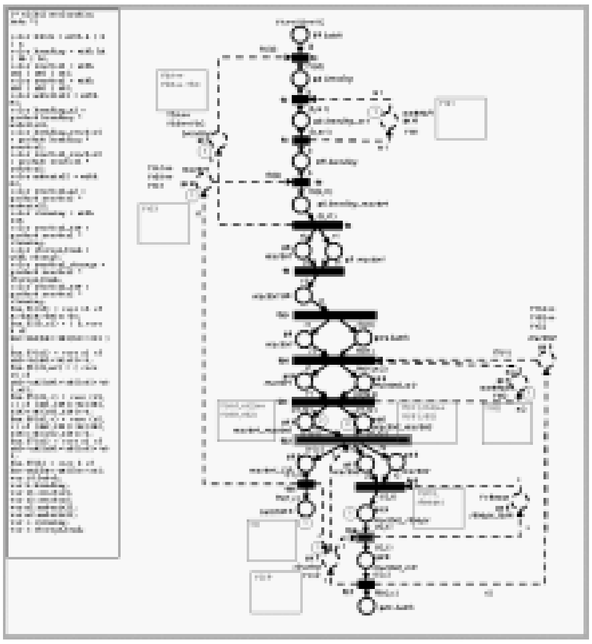

Fig. 7 A screenshot of simulation with Design/CPN

Table 1 Conflicts discovered through the simulation

Transition	Content
t2	Which path does a pipeline for #1 use?
t15	Which path does a pipeline for storage tank use?
t16	Which No.2 reactor does a CIP use?
t20	Which path does a pipeline for #2 use?
t22	Which No.1 reactor does a CIP use?

We applied the proposed modeling and analyzing method to a two-step polymer process already shown in Fig. 1. Following the method, a CPN model for batch sequential control system was generated as shown in Fig. 5. Figure 7 is a screenshot of Design/CPN corresponding to thus obtained model.

In order to discover conflicts, both structural analysis and simulation were carried out. Through the foregoing simulation methods, we could find all conflicts predicted by structural analysis. They are summarized in Table 1. There, *t*2, *t*15, and *t*22 are selectable-entity conflict, *t*16 and *t*22 are shared-resource conflict.

5. Conclusion

We propose a modeling and analyzing method for batch sequential control systems. For this purpose, a CPN model is generated by using information based on S88 and applied to the conflict analysis. Through the case study, we have verified the effectiveness of the method. Finally, we can conclude our approach is promising to provide a novel environment to model and analyze the batch sequential control systems.

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