Modeling and Simulation of Metallurgical Process Based on Hybrid Petri Net

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Abstract. In order to achieve the goals of energy saving and emission reduction of iron and steel enterprises, an increasing number of modeling and simulation technologies are used to research and analyse metallurgical production process. In this paper, the basic principle of Hybrid Petri net is used to model and analyse the Metallurgical Process. Firstly, the definition of Hybrid Petri Net System of Metallurgical Process (MPHPNS) and its modeling theory are proposed. Secondly, the model of MPHPNS based on material flow is constructed. The dynamic flow of materials and the real-time change of each technological state in metallurgical process are simulated vividly by using this model. The simulation process can implement interaction between the continuous event dynamic system and the discrete event dynamic system at the same level, and play a positive role in the production decision.

1. Introduction

Recently, the high speed development of the metallurgical industry brought enormous impact on resources, energy and environment [1]. Therefore, development of the new generation of Iron and Steel production process has become the primary problem of metallurgical industry. Due to the high complexity, high cost and high energy consumption of metallurgical process, modeling and simulation technology has become an important way to research and analyze the metallurgical process. At the present stage, there are many methods of metallurgical process modeling. The traditional standard material flow diagram [2], which only comprises the input and output flow of iron material, lacks analysis of all the production material and the dynamic evolution process of various materials. For the more, the Petri Net of Iron and Steel Process Based on Technological Indicators (ISPPNSTI) [3] is short of modeling the discrete event dynamic system in the metallurgical process, and it can’t show the interaction between the dynamic evolution of material and the change of technological state.

Metallurgical production process is a typical hybrid process which contains both continuous and discrete event systems [4]. In metallurgical production process, the Coking, Sintering and some other processes are continuous production process, which can be seen as continuous event dynamic system; the change of each technological state (running or idle), which is independent of each other, can be regarded as discrete event dynamic system. In order to simulate the metallurgical production process more accurately, an appropriate model of the process is necessary to reflect the discrete parts and continuous parts of metallurgical process, and achieve interaction between them.

Hybrid Petri net [5] is an extension of the traditional Petri net [6,7], which not only inherits the advantages of traditional Petri net in modeling, but also can achieve the interaction between discrete event dynamic system and continuous event dynamic system at the same level. A model of Hybrid Petri net is composed of discrete parts and continuous parts, and the two parts are connected to an Arc
between a discrete node and a continuous node. So that, the model can realize mutual influence between discrete portions and continuous portion in dynamic system. Therefore, the characteristics and modeling methods of Hybrid Petri net can be just used to analyze metallurgical process.

In this paper, we propose the definition and modeling theory of MPHPNS, and build the Hybrid Petri net system model of metallurgical process based on material flow by using the modeling algorithms. Through this model, we can clearly show the static structure of metallurgical process. Then we simulate the metallurgical production process by using this model, and analyze the simulation process, which can not only achieve the dynamic simulation of the whole production process, but also directly show the state of each technics.

2. Basic Concepts

2.1. Definition of Hybrid Petri Net System of Metallurgical Process

In MPHPNS, the continuous parts represent the flow of material resources; the discrete parts represent the change of technological state. The continuous places \(c P\) represent storage places of the material resources; the continuous transitions \(c T\) represent productive technics; Arcs \(F \subseteq \{(p', x, T)\}\) represent the flow-direction of material resources. The discrete places \(d T\) represent the state of technics (running or idle); the discrete transitions and the Arcs \(F \subseteq \{(p, x, T)\}\) lead to the change of technological state; the initial marking \(M_0\) represents the initial distribution of resources of places; the capacity function \(K\) represents the maximum of resources that the place can hold; the Arc labels \(W \in \{\text{Pre, Post}\}\) indicate the number of input or output resources in the reaction process. Accordingly, this model can be defined as a 6-tuple \(\mathcal{G}_{\text{sys}} = \{P, T, F, M, K, W\}\), where

- \(P = \{p_1, p_2, \ldots, p_n\} = \bigcup_{n \geq 0} \{p'\}\), a finite, not empty, set of places;
- \(T = \{t_1, t_2, \ldots, t_m\} = \bigcup_{m \geq 0} \{T'\}\), a finite, not empty, set of transitions;
- \(F = \{(p \times T) \cup (T \times p)\}\), a set of resources flow, \(\forall (p, x, p') \in \{F = \{(p \times t)\}\}\) need to satisfy \((t, x, T')\);
- \(M_0 : P \rightarrow R^{+} \cup N\), a set of the initial distribution of resources (initial marking);
- \(K : P \rightarrow \{1, 2, \ldots, k\} \in N^{+}\), capacity function;
- \(W = \{\text{Pre, Post}\}\), weight function;
- \(\text{Pre} : P \times T \rightarrow R^{+} \cup N\), weight between input places and transitions;
- \(\text{Post} : P \times T \rightarrow R^{+} \cup N\), weight between transitions and output places;

In the definitions of \(\text{Pre} \), \(\text{Post} \) and \(M_0 \), \(N\) corresponds to the case where \((p, x, p')\), and \(R^+\) corresponds to the case where \((p, x, t)\). \(\text{Pre} \) and \(\text{Post} \) function must meet the following criterion: if \(p_i\) and \(t_j\) are a place and a transition such that \((p_i, x, p')\) and \((t_j, x, T')\), then \(\text{pre}(p_i, t_j) = \text{post}(p_i, t_j)\) must be satisfied [6].

3. Modeling Theory

3.1. Modeling algorithms

The basic operations of Petri net [8] include insertion operation, deletion operation, and composition operation, which are the foundation of the model building. According to the modeling algorithms of Petri net and the definition of MPHPNS, the modeling algorithms of MPHPNS are established, which mainly include the insertion operation, deletion operation, and composition operation.

Note: The definition of inserting operation, deleting operation and composition operations we proposed above can be found in my master’s thesis (c.f. [9]).

3.2. Transition Trigger Rules
The fires of transition lead to the change of resources distribution of place, which plays a crucial role in analysing the dynamic evolution of the material and grasping the state of the technics in the actual production process.

**Theorem 1** The trigger condition of the transition can be described as follow, \( \forall t \in T, M[t] \geq \) on the condition of:

\[
\begin{align*}
& M(p) \geq Pre(p, t) \\
& M(p) + Pre(p, t) - Post(p, t) \leq K(p) \\
& M(p) + Post(p, t) \leq K(p)
\end{align*}
\]

(1)

**Theorem 2** The trigger result of the transition can be described as follow, if \( M[t] > M'[t] \), \( \forall p \in P \) obtains:

\[
M'(p) = \begin{cases}
M(p) - Pre(p, t) & p \in t - i' \\
M(p) + Post(p, t) & p = t' - i' \\
M(p) + Post(p, t) - Pre(p, t) & p = i(t)' \\
M(p) & \text{others}
\end{cases}
\]

(2)

Note: \( t \) represents the input position of \( (i) \) when transition are triggering; \( i' \) represents the output position of \( (i) \) when transition triggered; \( M[t] \geq \) indicates that the transition \( (i) \) can be fired in marking \( (M) \); \( M[t] > M' \) describes the result of a fired transition \( (i) \) in a new distribution of resources \( (M') \).

4. System Modeling

The traditional metallurgical process [10] is generally composed of Coking, Sintering, Blast furnace, Desulphurization pretreatment, Dephosphorization converter, Decarburization converter, Continuous casting, Hot-rolling and Storing. The idea of building the model of MPHPNS can be described as follows: firstly, each stage of productive technics is abstracted into a 6-tuple; secondly, build every stage model by using insertion and deletion operations; finally, integrate every stage model into a traditional metallurgical process by using composition operation.

According to the modeling process above, we can obtain the Hybrid Petri net system model of metallurgical process (as shown in Figure 1).

![Figure 1. The Hybrid Petri net model of metallurgical process](image-url)
expressed by double circle. In addition, the sub-technics model can be seen in my master's thesis (c.f [9]).

5. Process Simulation and Analysis

The model of MPHPNS we built above consists of two parts. One part is the continuous Petri net which is used to simulate the dynamic flow of materials resources, and the other part is the discrete Petri net which is used to simulate the change of the technological state in simulation process.

5.1. Process Simulation

Using this model, the simulation process is as follow: Firstly, all of the production technics are running. We can make sure that only the process of Coking can be fired (as shown in Figure 2) by analyzing the trigger condition of each transition in initial marking. Then, the process of Coking fires and leads to the change of resources distribution, which makes the only process of Sintering fire. It follows the process of Blast furnace, Desulphurization pretreatment, Dephosphorization converter, Decarburization converter, Continuous casting, Hot-rolling and Storing fires sequentially. Finally, the output is the corresponding steel, and then the process of Coking switches from running state to idle state because of the number of reactants are not abundant.

![Figure 2. The firing state of Coking](image)

The description of simulation process above can fully reflect the actual production of metallurgical process. It can clearly show the dynamic evolution process of material in each technics process, and describe the technological state at a certain point. At the same time, it can realize the cycle simulation of the whole production process under the condition of abundant material.

Note: In the simulated process, black represents that transitions can’t be triggered; red represents that transitions can be fired.

5.2. Process Analysis

The simulation process of the MPHPNS can complete the continuous flow of material and the change of technological state interaction at the same level. This interaction is mainly manifested in two parts. One side is the influence of the continuous part on the discrete part, which mainly performance in: when the initial material of a technics is not sufficient or a material space is insufficient, the technics will switch from running state to the idle state. The other side is the effects of the discrete part on the continuous part, which mainly performance in: when the technics is in idle state, the technics can’t be triggered.

Take Coking as an example. At first, the process of Coking fires, and changes the distribution of resources (as shown in Figure.3 (a)). Continue to perform process simulation, we can see that the Coking process is switched to the idle state (as shown in Figure.3 (b)) because of the lack of the number of reactant. At the same time, the process of Coking can’t be triggered.
When the material space is not enough to hold more generated materials, technics can also be switched to idle state. In the cycle simulation of production process, it can avoid to compete for the space of material places by the interaction between continuous and discrete parts. We can grasp the state of each technics in the first time through observing the discrete parts of model. So that we can more quickly and accurately find problems in the production process, which plays a positive role to the production decision.

6. Conclusions
The model of Hybrid Petri Net System of Metallurgical Process can exhibit the static structure of metallurgical process. The simulation process fully reflects the actual production of metallurgical process, and implements interaction between the dynamic continuous evolution of the material and the change of discrete state of technics at the same level. The modeling theory of Hybrid Petri Net System of Metallurgical Process provides a feasible and controllable method for modeling. However, the analysis of the model’s properties still needs further research and discussion.

7. References
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