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Operation Chain Model of Reconfigurable Printing Manufacturing System Based on Stochastic Process Algebra

HUAILIN LI [1,2,3], SHISHENG ZHOU [1,2,3,4], RUBAI LUO [2,3,4], AND BIN DU [2,3]
[1]Faculty of Mechanical and Precision Instrument Engineering, Xi'an University of Technology, Xi'an 710048, China
[2]Shaanxi Collaborative Innovation Center of Green Intelligent Printing and Packaging, Xi'an 710048, China
[3]Shaanxi Provincial Key Laboratory of Printing and Packaging Engineering, Xi'an 710048, China
[4]Faculty of Printing, Packaging Engineering and Digital Media Technology, Xi'an University of Technology, Xi'an 710048, China

Corresponding author: Huailin Li (lihuailin6666@sina.com)

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ABSTRACT When printing orders change, the reconfigurable printing manufacturing system (RPMS) needs to be reconfigured, which produces many feasible reconfiguration schemes. To find the optimal reconfiguration scheme and verify its integrity, an operation chain model (OCM) of an RPMS is proposed to describe the operating process of an RPMS. First, a comprehensive evaluation algorithm considering both subjective and objective evaluation probabilities is designed by analyzing the characteristics of the printing production process. Then, the syntax of stochastic process algebra is conservatively extended to meet the operation chain's specifications. The syntax and transition rules of the OCM are defined and the semantic model of the operation chain is constructed. Finally, we carried out experiments on the RPMS of a printing enterprise and provide the experimental results. The results show that the optimal printing scheme that is selected by the OCM is in line with expectations. In addition, the measurement result $I_{CP} = true$ shows that the optimal reconfigurable printing scheme process has good integrity.

INDEX TERMS Reconfigurable printing manufacturing system, comprehensive evaluation algorithm, stochastic process algebra, operation chain model, integrity measurement.

I. INTRODUCTION

With the continuous improvement of living standards and technology, people tend to customize and diversify products. Traditional small and medium-sized printing companies do not have the ability to adapt to rapid market changes because of their single production mode and fewer types of products. Printing enterprises are under great pressure to survive. Therefore, the printing industry is looking for a production mode that can respond quickly to market changes and improve the production capacities of printing enterprises. The reconfigurable printing manufacturing system (RPMS) has this capability.

Reconfigurable techniques can effectively improve the reliability, flexibility and robustness of manufacturing systems [1]. Previously, we used basic process algebra as a basis for studying the reconfiguration mechanism of an RPMS and discussed its flexibility and security [2], [3]. However, there may be many feasible reconfiguration schemes after the system reconfiguration. The existing RPMS cannot make decisions on the optimal reconfiguration printing scheme, and it cannot verify the integrity of the system's functions. The reason is that basic process algebra ignores the temporal relationship and the uncertainty of entity behavior in the model, which limits the model's capabilities. Based on basic process algebra, stochastic process algebra (SPA) adds some performance characteristics such as time and probability. Its variations include Performance Evaluation Process Algebra (PEPA) [4], Timed Processes Performance Evaluation (TIPP) [5], and Extended Markovian Process Algebra (EMPA) [6]. The fluid approximation when applying PEPA models has been intensively discussed in [7]–[9] and [10]. Srivastava and Banicescu used SPA to obtain the performances of various resource allocations [11]. To solve the

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problem of state space explosion, Ding et al. proposed the timed state equation for SPA models [12]. SPA effectively improves the model's capabilities and lays the foundation for the quantitative and qualitative analyses of the model.

Many researchers have conducted in-depth research in order to solve the problems of reconfiguration schemes [13]–[16]. Pinkston *et al.* [13] and Wang *et al.* [16] introduced an evaluation method to evaluate the reconfiguration scheme. A comprehensive evaluation method was used for monitoring energy management systems [17], improving hotel service quality [18], scheduling virtual machine migration [19] and selecting the most preferred service [20]. In this paper, we propose a comprehensive evaluation method considering both subjective and objective evaluations to calculate the probability of selecting the optimal reconfiguration scheme. Therefore, this paper takes the RPMS as the research object and studies its optimal printing scheme and integrity based on SPA.

Following the introduction section, the rest of this paper is formed as follows. Section II introduces SPA terminology and its characteristics. In Section III, we propose a comprehensive evaluation method of an RPMS reconfiguration scheme, which mainly includes the subjective evaluation method and the objective evaluation method. Based on SPA, the syntax and transition rules of the operation chain model (OCM) are defined and the semantic model of the operation chain is constructed in Section IV. The RPMS of a printing enterprise is used as an example to illustrate the contributions in Section V. We conclude with some conclusions and considerations for further research in Section VI.

II. STOCHASTIC PROCESS ALGEBRA

Process algebra is a formal modeling language for describing complex concurrent systems. Hoare's Communication Sequential Process (CSP) [21], Milner's Communication Calculus System (CCS) [22] and Fokkink's Introduction to Process Algebra [23] are the most widely used. To model spatiotemporal behavior, Zhang et al. proposed the qualitative CSP as a formal language [24]. Process algebra cannot be quantitatively analyzed. However, SPA inherits the formal description approach from the classic process algebra for the system model. In addition to providing precise formal semantics and strict mathematical bases for the system model's verification, SPA adds the time and probability parameters to each activity of the system model. SPA can verify the security and robustness of the external behavior of the system model, solve the optimal scheme selection problem and verify its integrity.

In the application of SPA to manufacturing system modeling, the SPA analysis methods mainly include two aspects: quantitative analysis and qualitative analysis. Similar to classic process algebra, the qualitative analysis method only focuses on whether the processing function of the system model meets the requirements of customers, and it does not pay attention to the processing time and efficiency of the system model. However, quantitative analysis focuses on the

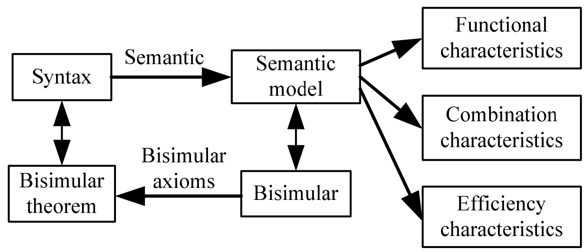

FIGURE 1. The SPA system framework.

description and analysis of the manufacturing behavior and the optimal scheme selection. After analyzing the material flow, information flow and data flow among the system's manufacturing cells, we can obtain the time parameters of the system model, such as the ramp-up time and stable operation time. Thus, the performance evaluation parameters are obtained and combined with the evaluation indexes of the reconfigurability, economy, reliability and man-machine relationship of the manufacturing system. The SPA system framework is shown in Figure 1. In summary, SPA focuses on the following characteristics of manufacturing systems.

1) Functional characteristics: flexible and deadlock.

2) Combination characteristics: the probability of timeout and the execution time of certain sequential activities.

3) Efficiency characteristics: throughput, ramp-up time and stable operation time.

The SPA syntax defines two basic elements: components and activity. Its system framework consists of the syntax, semantic model, axiom system and model analysis [25]. The SPA syntax defines the activities of the components by defining the operators, and the concurrent behavior among components builds the complex systems. By using structural operational semantics and the semantic model, the transition rules of components in different states are defined. These transition rules constitute the axiom system of SPA. The model analysis mainly focuses on the quantitative and qualitative analyses of the security, flexibility, robustness, optimality and integrity of the complex system. In this paper, we conduct qualitative and quantitative analyses of the optimal printing scheme and the integrity of the RPMS based on SPA.

III. COMPREHENSIVE EVALUATION METHOD

An RPMS can be divided into three stages: pre-printing, printing and post-printing. Pre-printing mainly completes the preparations before printing, and its process includes the proof, typeset, plate making and so on. Printing is the process of transferring the picture and text information from the original manuscript to the substrate by using the printing equipment. Post-printing mainly completes the decoration of printed matter, such as folding, binding, cutting and so on. The RPMS of a printing enterprise is shown in Figure 2. The modular design is an important feature of the RPMS. Because the printing equipment can be upgraded and expanded, they

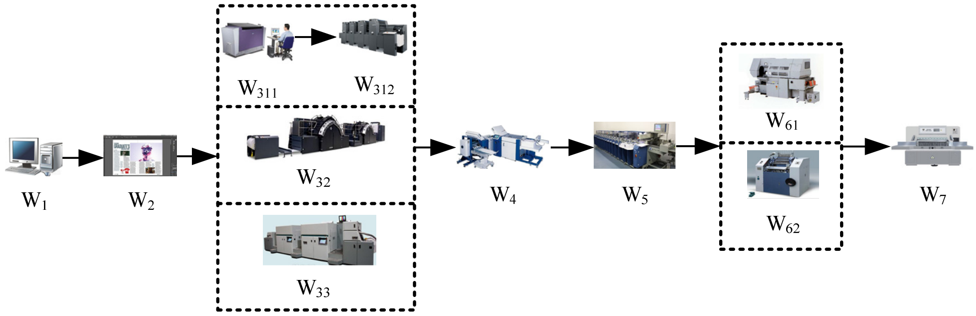

FIGURE 2. Reconfigurable printing manufacturing system.

TABLE 1. The printing manufacturing modules corresponding to the RPMS.

Stage	Process	Symbol	Printing manufacturing module
Pre-printing	Preflight	W_1	Founder pod
	Typeset	W_2	KODAK Preps7.0
	Plate making	W_{311}	Kodak Prosper CTP 800III
Printing	Offset printing	W_{312}	Heidelberg 4 Colors Opposite Offset Printer CD102
	Rotary inkjet printing	W_{32}	HP Inkjet Rotary 4 Colors Printer T-300
	Inkjet printing	W_{33}	Océ JetStream Digital Inkjet Color Printer 1100
Post-printing	Folding	W_4	Automatic Folding Machine KDM 78T
	Collating	W_5	Automatic Collating Machine G460B/12
	Binding	W_{61}	Automatic Binding Machine BQ-470
		W_{62}	Automatic Sewing Binding Machine SXT-460
	Three-knife Trimmer	W_7	Three-knife Trimmer HL-QSS300

have modular characteristics. A printing equipment or a set of printing equipment with certain processing functions is called the printing manufacturing module. The printing manufacturing modules corresponding to the RPMS symbols in Figure 2 are given in Table 1.

The reconfigurable precondition of a printing manufacturing system is that the products of the former printing manufacturing module can be consumed by the latter module. In other words, the interface (resource) must be matched. However, it results in multiple printing manufacturing modules matching the resources of the former module, as shown in Figure 2. In the printing stage, the offset printing machine

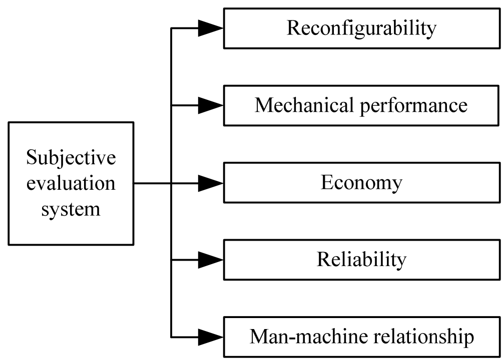

FIGURE 3. The subjective evaluation system of a printing manufacturing module.

W_{312} (it needs to be used with CTP machine W_{311}), the rotary inkjet digital printing machine W_{32} and the inkjet digital printing machine W_{33} are used to meet the requirements of the printing order. In the post-printing stage, there are two binding modes, the adhesive binding W_{61} and the thread sewing machine W_{62}, that are to meet the requirements of the printing order. Therefore, there are six printing reconfiguration schemes in Figure 2 that can meet the requirements of the printing order. How to determine the optimal printing reconfiguration scheme is the one of the keys of printing enterprise management.

At present, most printing enterprises do not have a good solution to the optimal scheme selection problem for an RPMS. They arrange production schemes based on the experience of the printing supervisor or order manager, but this scheme sometimes has some disadvantages, such as wasted resources, high costs, lower production efficiency and a suboptimal rate of equipment utilization. Therefore, this paper proposes a comprehensive evaluation method for an RPMS reconfiguration scheme. The comprehensive evaluation method mainly includes two parts: the subjective evaluation method and the objective evaluation method.

A. SUBJECTIVE EVALUATION METHOD

The subjective evaluation system of the printing manufacturing module in the RPMS reconfiguration scheme is shown in Figure 3. The evaluation indexes of the subjective evaluation system mainly consider reconfigurability, the mechanical performances of the printing manufacturing module, economy, reliability and man-machine relationship.

Reconfigurability: The reconfigurability of the printing manufacturing module depends on the extensibility and integration of the function and structure. The stronger the extensibility and integration are, the better the reconfigurability of the printing manufacturing module.

Mechanical performance: This refers to the processing types, the utilization rate and the production efficiency of the printing manufacturing module.

Economy: This mainly considers factors such as the maintenance costs of the printing manufacturing module, the human and material costs and environmental protection.

Reliability: This needs to consider two factors: the ramp-up time and the average failure time of the printing manufacturing module. The ramp-up time is the time from the reconfiguration of the printing manufacturing modules to the stable operation of the RPMS. The shorter the ramp-up time and average failure time are, the better the reliability.

Man-machine relationship: The relationship between the printing manufacturing module and operators mainly involves the security of the system and the operational complexity. The lower the required operator abilities for the printing manufacturing module are, the better the man-machine relationship. In other words, the operators feel safe and comfortable when they operate these printing machines.

In this paper, based on the subjective evaluation system for the printing manufacturing module in the RPMS reconfiguration scheme, a few experienced printing practitioners score the different printing manufacturing modules. The average score of each evaluation index is calculated for the printing manufacturing module, as shown in formula (1).

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{1}$$

where $\bar{x}$ denotes the average score of an evaluation index, n is the number of scorers, and x_i is the score that is given by the i-th experienced printing practitioner.

The ratio between the sum of all average evaluation index scores to the full score is taken as the subjective evaluation probability of the printing manufacturing module, as shown in formula (2).

$$p_s = \frac{\sum_{k=1}^{m} \overline{x_k}}{10m} \tag{2}$$

where p_s denotes the subjective evaluation probability,m is the number of subjective evaluation indexes, and $\overline{x_k}$ represents the average score of the k-th subjective evaluation index.

B. OBJECTIVE EVALUATION METHOD

According to the design of the subjective evaluation method's algorithm, we can conclude that it relies on the knowledge and experience of the scorer, and it is easily influenced by the scorer's mood and interests. Therefore, it is unscientific to evaluate the quality of a printing manufacturing module using only the subjective evaluation probability. For this reason, we also design an objective evaluation method, which mainly includes the production costs and processing time. Because the RPMS responds more rapidly to unpredictable market changes, the processing time of the printing manufacturing module is mainly considered in this paper. The formula for calculating the processing time is as follows:

$$T = T_{tu} + T_{run} \tag{3}$$

where T represents the printing processing time of a printing manufacturing module,T_{tu} represents the ramp-up time of the printing manufacturing module, and T_{run} represents the stable running time of the printing manufacturing module.

A short processing time indicates that the printing manufacturing module is highly efficient. Therefore, the objective evaluation probability design of the manufacturing module is calculated as follows:

$$p_o = 1 - \frac{T_i}{\sum_{i=1}^{n} T_i} \tag{4}$$

where p_o denotes the objective evaluation probability, T_i represents the processing time of the i-th printing manufacturing module, and n is the number of printing manufacturing modules in the same process.

C. COMPREHENSIVE EVALUATION METHOD

Based on the subjective and objective evaluation method, the comprehensive evaluation method of an RPMS is introduced in this section. The comprehensive evaluation probability of the printing manufacturing module is the weighted sum of the subjective and objective evaluation probability, as shown in formula (5).

$$r' = \omega_1 p_s + \omega_2 p_o \tag{5}$$

where $\omega_1 + \omega_2 = 1, 0 < \omega_1 < 1, 0 < \omega_2 < 1$, r' denotes the comprehensive evaluation probability, ω_1 denotes the weight value of subjective evaluation and ω_2 denotes the weight value of objective evaluation.

IV. OPERATION CHAIN MODEL

The interaction process mainly includes two parts: one is the interaction process between the printing manufacturing module and the control platform (CP), and the other is the interaction process between the CP and the database (DB), as shown in Figure 4. In this section, first, the integrity attributes, the integrity measurement probability and the comprehensive evaluation probability are extended using the SPA syntax. Second, the transition rules of the operating chain model are designed on this basis. Finally, a semantic model of the operation chain is established by setting the printing manufacturing modules, CP and DB in parallel.

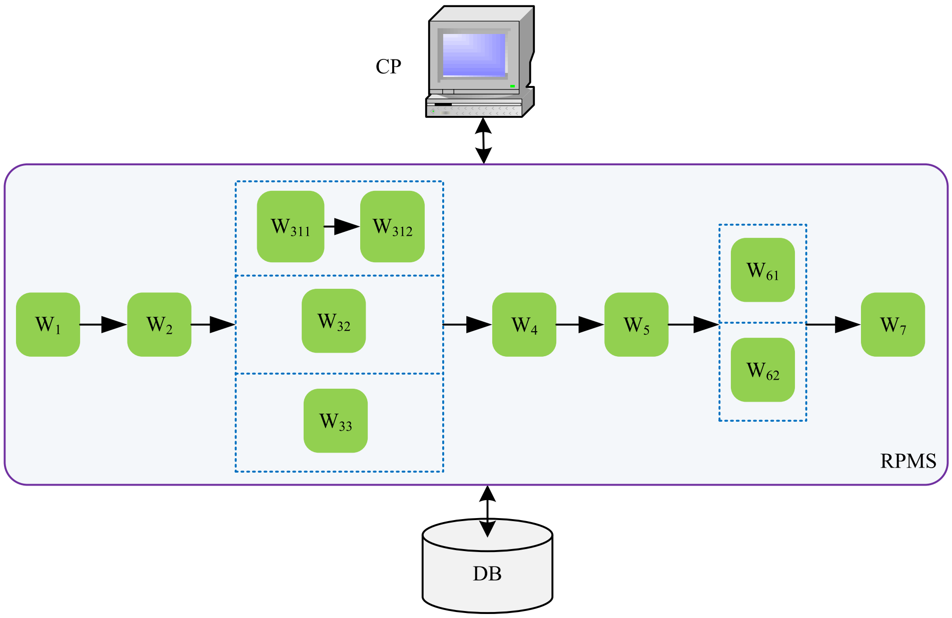

FIGURE 4. The operating chain of a reconfigurable printing manufacturing system.

A. SYNTAX

Based on SPA, the syntax defines the components, activities, atomic actions and operators for the OCM of RPMS.

Definition 1 Components: Several printing manufacturing modules, including the CP and DB, are called components, as shown in formula (6). Some printing manufacturing modules of the RPMS are represented as $W_1, W_2, W_3 \cdots W_n$.

$$Q = \{CP, DB, W_1, W_2, W_3 \cdots W_n\} \tag{6}$$

Definition 2 Atomic action: The actions that are executed by components are called atomic actions, as shown in formula (7). The atomic actions are indivisible in the components of the system.

$$\begin{aligned} act &= \{act_{CP}, act_W, act_{DB}\} \\ act_{CP} &= \{extending, extended, completed, idle_{CP}\} \\ act_W &= \{run, measure, transfer, extending, idle_W\} \\ act_{CP} &= \{transfer, save, idle_{DB}\} \end{aligned} \tag{7}$$

Here, *extending* represents that the manufacturing modules of the RPMS are expanding through their interfaces, *extended* represents the completion of the *extending* activity, *completed* represents the completion of the selection and measurement of the optimal reconfiguration scheme, $idle_{CP}$ represents that the CP is idle, *run* represents the analog operations of the printing manufacturing module, *measure* represents that the CP measures the integrity of the manufacturing module, *transfer* represents the communications between the CP and DB, $idle_W$ represents that the printing manufacturing module is idle, *save* represents that the CP saves the optimal manufacturing module to the DB, and $idle_{DB}$ represents that the DB is idle.

Definition 3 Activity: A component activity is composed of a quintuple $\left(a, I_q, r, T_q, r^{'}\right)$.

$$\begin{aligned} activity &= \left(a, I_q, r, T_q, r^{'}\right) \\ I_q &= \begin{cases} false & r = 0 \\ true & r = 1 \end{cases} \end{aligned} \tag{8}$$

where $a \in act$, $q \in Q$, I_q describes the integrity of component Q when the activity a is executed, $I_q = false$ means that the printing manufacturing module does not possess integrity, and $I_q = true$ means that the printing manufacturing module possesses integrity. r denotes the probability of measuring Q components' integrity, where $r \in \{0, 1\}$. T_q refers to the activity time of the printing manufacturing module. $r^{'}$ represents the comprehensive evaluation probability of the printing manufacturing module. According to $r^{'}$, the optimal printing scheme of the RPMS can be determined.

Definition 4 Operator: This refers to the relationships among components such as cooperation, competition and synchronization, as shown in formula (9). The complex systems can be composed of components using the operators.

$$Q ::= Nil| \left(a, I_Q, r, T_Q, r^{'}\right).Q|Q+P|Q \parallel_L P|Q/H|A \stackrel{\text{def}}{=} Q \tag{9}$$

Deadlock: *Nil* means that the integrity verification stops and is deadlocked. In other words, the RPMS is incomplete.

Prefix: $\left(a, I_Q, r, T_Q, r^{'}\right).Q$ means that $\left(a, I_Q, r, T_Q, r^{'}\right)$ is executed first before executing component Q.

Choice: $Q + P$ means that the system executes component Q or component P. For example, component $W_2 + W_3$ means that printing manufacturing modules W_2 or W_3 can complete their processing tasks, and this is a competitive relationship. The RPMS finally chooses the better one to execute, either W_2 or W_3.

Parallel: $Q \parallel_L P$ means that the activities of component Q and component P must be synchronously executed if they belong to set L, and they are independently and concurrently executed if they are not in set L. The relationship between components Q and P is cooperative and synchronous. For example, for a set $L = \{extending\}$, CP $\parallel_L W$ means that the CP and the printing manufacturing module W must cooperatively execute the *extending* activity.

Hiding: Q/H represents that the activities are invisible for the external observer when component Q executes it activities in set H.

Recursive: $A \overset{\text{def}}{=} \left(a, I_Q, r, T_Q, r'\right).Q$ represents that the activity $\left(a, I_Q, r, T_Q, r'\right)$ is executed in an infinite loop.

B. TRANSITION RULE

To select the optimal scheme of the RPMS and verify its integrity, five transition rules of the OCM are designed based on SPA.

Rule 1: Transition rule of the prefix operator

The transition rule of the prefix in SPA is shown as follows:

$$(a, I_Q, r, T_Q, r').Q \xrightarrow{(a, I_Q, r, T_Q, r')} Q \tag{10}$$

The CP verifies the integrity of the RPMS by measuring the integrity of each of the printing manufacturing modules using probability r. The state transition rule of the integrity is written as follows.

$$I_{CP} \to I_{CP} \oplus I_Q \tag{11}$$

where I_{CP} denotes the integrity of the RPMS. $I_{CP} = false$ means that the RPMS has no integrity, and $I_{CP} = true$ means that the RPMS has good integrity. The initial state of I_{CP} is set as *true*. $\oplus$ is designed as a Boolean operator, which is shown as follows.

$$I_{CP} \oplus I_Q = \begin{cases} false, & r = 0 \\ true, & r = 1 \end{cases} \tag{12}$$

The transition rule for the conservative extension of the prefix operator is shown as follows.

$$\frac{I_{CP} = true \,\&\, T_{CP} = 0}{\begin{array}{c}\left(a, I_Q, r, T_Q, r'\right).Q \xrightarrow{\left(a, I_Q, r, T_Q, r'\right)} Q \\ I_{CP} \to I_{CP} \oplus I_Q \\ T_{CP} = T_{CP} + T_Q\end{array}} \tag{13}$$

Rule 2: Transition rule of the choice operator

When the comprehensive evaluation probability of component Q is larger than that of component P ($r'_Q > r'_P$), component Q is chosen to be executed, as shown in formula (14). In contrast, when the comprehensive evaluation probability of component P is greater than that of component Q ($r'_P > r'_Q$), component P is chosen to be executed, as shown in formula (15). The optimal scheme can be determined by comparing the comprehensive evaluation probabilities of the manufacturing modules. Similarly, the prerequisite of the choice transition rule is $I_{CP} = true$.

$$\frac{I_{CP} = true \,\&\, r'_Q > r'_P}{\begin{array}{c} Q + P \xrightarrow{\left(a, I_Q, r, T_Q, r'_Q\right)} Q' \\ I_{CP} \to I_{CP} \oplus I_Q \end{array}} \tag{14}$$

$$\frac{I_{CP} = true \,\&\, r'_P > r'_Q}{\begin{array}{c} Q + P \xrightarrow{\left(a, I_P, r, T_P, r'_P\right)} P' \\ I_{CP} \to I_{CP} \oplus I_Q \end{array}} \tag{15}$$

Rule 3: Transition rule of the parallel operator

If $a \notin L$ or $L = \Phi$, the CP measures the integrity of component Q or component P using probability r. The transition rule of the parallel operator is shown as follows. Similarly, the prerequisite of the transition rule is $I_{CP} = true$.

$$\frac{I_{CP} = true \,\&\, Q \xrightarrow{\left(a, I_Q, r, T_Q, r'_Q\right)} Q'}{\begin{array}{c} Q \parallel_L P \xrightarrow{\left(a, I_Q, r, T_Q, r'_Q\right)} Q' \\ I_{CP} \to I_{CP} \oplus I_Q \end{array}} (a \notin L) \tag{16}$$

$$\frac{I_{CP} = true \& P \xrightarrow{\left(a, I_P, r, T_P, r'_P\right)} P'}{\begin{array}{c} Q \parallel_L P \xrightarrow{\left(a, I_P, r, T_P, r'_P\right)} P' \\ I_{CP} \to I_{CP} \oplus I_P \end{array}} (a \notin L) \tag{17}$$

Similarly, the prerequisite of the parallel transition rule is $I_{CP} = true$. If component Q and component P successfully transit to Q' and P', $a \in L$, and $L \notin \Phi$, the CP measures the integrity of components Q and P using probability r. The transition rule of the parallel operator is shown as follows (18), as shown at the bottom of the next page.

Rule 4: Transition rule of the recursive operator

Similarly, the prerequisite of the recursive transition rule is $I_{CP} = true$. Component Q successfully transits to Q'. The transition rule of the recursive operator is shown as follows.

$$\frac{I_{CP} = true \,\&\, Q \xrightarrow{\left(a, I_Q, r, T_Q, r'_Q\right)} Q'}{\begin{array}{c} A \xrightarrow{\left(a, I_Q, r, T_Q, r'_Q\right)} Q' \\ I_{CP} \to I_{CP} \oplus I_Q \end{array}} \left(A \overset{\text{def}}{=} Q\right) \tag{19}$$

Rule 5: Transition rule of the deadlock operator

If the integrity verification of the CP extends to an incomplete component Q ($I_Q = false$) and component Q executes any activities, the verification immediately falls into deadlock. The transition rule of the deadlock operator is shown as follows.

$$\frac{I_{CP} = true \,\&\, I_Q = false}{\begin{array}{c} \left(a, I_Q, r, T_Q, r'_Q\right).Q \xrightarrow{\left(a, I_Q, r, T_Q, r'_Q\right)} Nil \\ I_{CP} \to false \end{array}} \tag{20}$$

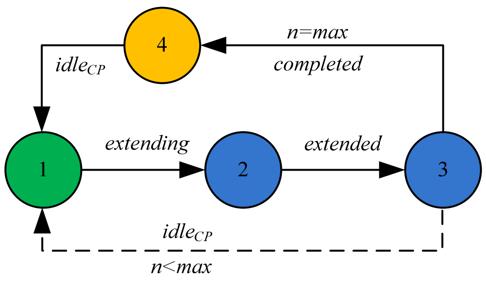

FIGURE 5. State transition of the control platform.

C. SPA-BASED OPERATING CHAIN MODEL

1) SEMANTIC MODEL OF THE CP

In the process of selecting the optimal reconfiguration scheme of the RPMS and verifying its integrity, the main activities of the CP are *extending* and *extended*. When the last printing manufacturing module is verified, *completed* is executed. Finally, the CP is idle ($idle_{CP}$). Therefore, the semantic model of the CP is constructed as shown in formula (21). The state transition graph of the CP is shown in Figure 5.

$$CP \overset{\text{def}}{=} \left(extending, I_{CP}, r, T_{CP}, r'_{CP}\right) \cdot \left(extended, I_{CP}, r, T_{CP}, r'_{CP}\right) \cdot \left(idle_{CP}, I_{CP}, r, T_{CP}, r'_{CP}\right) \cdot CP + \left(extending, I_{CP}, r, T_{CP}, r'_{CP}\right) \cdot \left(extended, I_{CP}, r, T_{CP}, r'_{CP}\right) \cdot \left(completed, I_{CP}, r, T_{CP}, r'_{CP}\right) \cdot \left(idle_{CP}, I_{CP}, r, T_{CP}, r'_{CP}\right).CP \quad (21)$$

2) SEMANTIC MODEL OF THE PRINTING MANUFACTURING MODULE

The printing manufacturing module of the RPMS first *runs*, and then the CP measures the integrity of this module. When $I_{W_n} = false$, the measurement result shows that the RPMS is incomplete, and the verification falls into deadlock (*Nil*) and immediately stops. It means that the RPMS is incomplete ($I_{CP} = false$). The printing manufacturing module becomes idle ($idle_{W_n}$). When $I_{W_n} = true$, the measurement result reflects integrity and outputs this printing manufacturing module to the database. Next, it communicates with the CP to verify the next module by *extending*. Finally, the printing manufacturing module is idle. The semantic model of the printing manufacturing module is shown in formula (22).

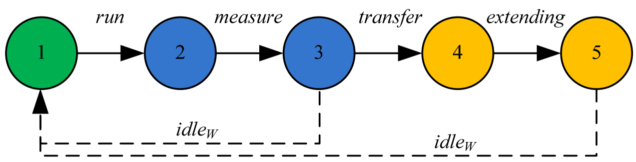

FIGURE 6. State transition of the printing manufacturing module.

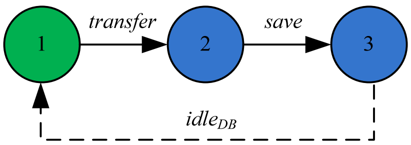

FIGURE 7. State transition of the database.

$$W_n \overset{\text{def}}{=} \times \left(run, I_{W_n}, r, T_{W_n}, r'_{W_n}\right) \cdot \left(measure, I_{W_n}, r, T_{W_n}, r'_{W_n}\right) \cdot \left(idle_{W_n}, I_{W_n}, r, T_{W_n}, r'_{W_n}\right).W_n + \left(run, I_{W_n}, r, T_{W_n}, r'_{W_n}\right) \cdot \left(measure, I_{W_n}, r, T_{W_n}, r'_{W_n}\right) \cdot \left(tranfer, I_{W_n}, r, T_{W_n}, r'_{W_n}\right) \cdot \left(extending, I_{W_n}, r, T_{W_n}, r'_{W_n}\right) \cdot \left(idle_{W_n}, I_{W_n}, r, T_{W_n}, r'_{W_n}\right).W_n \quad (22)$$

The state transition graph of the printing manufacturing module is shown in Figure 6.

3) SEMANTIC MODEL OF THE DB

The main function of the DB is to store the optimal reconstruction scheme. The main activities of the DB are *transfer* and *save*. The rest of the time is idle ($idle_{DB}$). The semantic model of the DB is shown in formula (23).

$$DB \overset{\text{def}}{=} \times \left(transfer, I_{W_n}, r, T_{W_n}, r'_{W_n}\right) \cdot \left(save, I_{W_n}, r, T_{W_n}, r'_{W_n}\right) \cdot \left(idle_{DB}, I_{W_n}, r, T_{W_n}, r'_{W_n}\right).DB \quad (23)$$

The state transition graph of the DB is shown in Figure 7.

4) SEMANTIC MODEL OF THE OCM

Based on the semantic model of the CP, printing manufacturing module and DB, this paper establishes the semantic

$$\frac{I_{CP} = true \,\&\, Q \xrightarrow{\left(a, I_Q, r, T_Q, r'_Q\right)} Q' \,\&\, P \xrightarrow{\left(a, I_P, r, T_P, r'_P\right)} P'}{Q \parallel_L P \xrightarrow{\left(a, I_Q, r, T_Q, r'_Q\right) \& \left(a, I_P, r, T_P, r'_P\right)} Q' \parallel_L P'} (a \in L)$$
$$I_{CP} \rightarrow I_{CP} \oplus I_Q$$
$$T_{CP} = T_{CP} + T_Q \quad (18)$$

TABLE 2. The evaluation score of the printing manufacturing module.

module	Reconfigurability	Mechanical performance	Economy	Reliability	Man-machine relationship
W_{31}	7.2	8.8	9.0	7.6	6.4
W_{32}	8.4	8.6	9.0	7.8	8.8
W_{33}	9.0	8.6	8.8	8.4	9.4
W_{61}	8.2	8.8	8.4	8.6	7.8
W_{62}	8.2	6.4	7.6	7.4	7.6

model of the OCM, as shown in formula (24). In this model, the semantic model of the CP and the printing manufacturing module must cooperate to execute the *extending* activity. Similarly, the semantic model of the printing manufacturing module and DB must cooperate to execute the *transfer* activity.

$$OCM = \left(W_1 \| W_2 \| W_3 \| \cdots \| W_n\right) \|_{\{extending\}} \times CP \|_{\{transfer\}} DB \qquad (24)$$

V. EXPERIMENTS

A. CALCULATION OF THE COMPREHENSIVE EVALUATION PROBABILITY

To select the optimal printing scheme and verify the integrity of the RPMS, we carry out experiments using the existing RPMS of a printing plant. There is an order for printing color books. The order size is 2000 volumes, the size of the pages is 245 × 175 mm, there are 160 pages per volume, and there is an unlimited binding style. The reconfiguration schemes of the RPMS are shown in Figure 2. It should be noted that W_{31} represents the offset printing style. Since the offset printing style requires plates, the offset printing process includes two parts: the CTP machine W_{311} and the offset press machine W_{312}.

To obtain the subjective evaluation score of the printing manufacturing module, we designed a subjective evaluation score table for the printing manufacturing modules of the RPMS (see Table 1s). Five experienced printing practitioners participated in the survey, including two researchers from the School of Printing and Packaging, a manager, a captain, and a technical researcher in the printing enterprise.

According to main technical parameters of the printing manufacturing modules (see Table 2s), the five experienced printing practitioners scored the printing manufacturing module. The average score was taken as the evaluation index. According to formula (1), each evaluation index of the manufacturing module was calculated as shown in Table 2. It should be pointed out that W_{311} and W_{312} of the offset printing style are evaluated as a whole in the subjective evaluation method.

Using Table 2 and formula (2), the subjective evaluation probability of each printing manufacturing module is calculated and shown in Table 3.

TABLE 3. The subjective evaluation probability.

Subjective evaluation probability	Printing manufacturing module				
	W_{31}	W_{32}	W_{33}	W_{61}	W_{62}
p_s	0.78	0.852	0.884	0.836	0.744

Table 4 gives the main technical parameters of each printing module in the RPMS.

Based on the technical parameters of each manufacturing module in Table 4, it can be seen that the technical parameters of all manufacturing modules can meet the processing requirements. Using the maximum processing size, we can design the printing layout to improve printing efficiency. Therefore, when we calculate the processing time of a printing manufacturing module, besides the printing speed, we also use the maximum processing size. According to the maximum processing size and the printing speed in Table 4, the theoretical results of time calculation for processing 2000 color books are shown in Table 5.

Using Table 5 and formulas (3) and (4), we calculate the objective evaluation probability of the printing manufacturing module as shown in Table 6.

Since the RPMS responds quickly to unpredictable market changes and the printing cost differences are not large, this paper mainly considers the processing time T. Therefore, the subjective evaluation weight is less than the objective evaluation weight: $\omega_1 = 0.3$ and $\omega_2 = 0.7$. Using Tables 3 and 6 and formula (5), we can calculate the comprehensive evaluation probability of each printing manufacturing module, as shown in Table 7.

From Table 7, it is easy to see that the best printing stage choice is the inkjet digital printer W_{33}, and the best post-printing stage choice is the binding machine W_{61}.

B. VERIFICATION OF OPERATION CHAIN MODEL

Based on the syntax and transition rules of the OCM semantic model, the OCM of the printing enterprise's RPMS is established, as shown in formula (25).

$$OCM = ((W_1 \| W_2 \| ((W_{311} \| W_{312}) + W_{32} + W_{33}) \| \times W_4 \| W_5 \| (W_{61} + W_{62}) \| W_7) \|_{\{extending\}} \times CP \|_{\{transfer\}} DB)/H \qquad (25)$$

TABLE 4. Technical parameters of the printing manufacturing module.

Printing manufacturing module	Name	Model	Speed	Maximum Processing size
W_{311}	Kodak Prosper	CTP 800III	40 sheets/h	1143×838 mm
W_{312}	Heidelberg 4 Colors Opposite Offset Printer	CD102	2500 cycles/min	1020×760 mm
W_{32}	HP Inkjet Rotary 4 Colors Printer	T-300	122 m/min	Width: 739 mm
W_{33}	Océ JetStream Digital Inkjet Color Printer	1100	1026 A_4/min（2-up）	279×216 mm
W_{61}	Automatic Binding Machine	BQ—470	22.5 copies/min	320×320 mm
W_{62}	Automatic Sewing Machine	SXT-460	4.5 copies /min	460×460 mm

TABLE 5. Processing time of each printing manufacturing module.

Processing time/min	Printing manufacturing module					
	W_{31}		W_{32}	W_{33}	W_{61}	W_{62}
	W_{311}	W_{312}				
T_{tu}	5	70	8	5	5	5
T_{run}	60	80	170	156	89	445
T_i	215		178	161	94	450

TABLE 6. The objective evaluation probability.

Objective evaluation probability	Printing manufacturing module				
	W_{31}	W_{32}	W_{33}	W_{61}	W_{62}
p_o	0.612	0.679	0.709	0.827	0.173

TABLE 7. The comprehensive evaluation probability.

Comprehensive evaluation probability	Printing manufacturing module				
	W_{31}	W_{32}	W_{33}	W_{61}	W_{62}
r'_W	0.662	0.731	0.762	0.830	0.344

where

$$H = \{extended, idle_{CP}, measure, idle_W, save, idle_{DB}\}$$

and

$$L = \{extending, transfer\}.$$

In the investigation of the printing manufacturing module in the printing plant, it is found that except for W_{33} that is under maintenance ($I_{W_{33}} = false$), all other modules are normal state ($I_{W_n} = true$). According to the main technical parameters in Table 3s, we can calculate the processing time of all printing manufacturing modules. The calculation process of the processing time is given in Table 4s. The component values of the activities for the printing manufacturing modules are given as shown in Table 8.

For example, the semantic models W_{31}, W_{32}, W_{33}, W_{61} and W_{62} can be obtained as follows in formula (26).

$$\begin{aligned}
W_{31} &\overset{\text{def}}{=} (run, true, 1, 215, 0.662).W_{31} \\
W_{32} &\overset{\text{def}}{=} (run, true, 1, 178, 0.731).W_{32} \\
W_{33} &\overset{\text{def}}{=} (run, false, 0, 161, 0.762).W_{33} \\
W_{61} &\overset{\text{def}}{=} (run, true, 1, 94, 0.830).W_{61} \\
W_{62} &\overset{\text{def}}{=} (run, true, 1, 450, 0.344).W_{62}
\end{aligned} \tag{26}$$

Because the manufacturing module W_{33} is under maintenance ($I_{W_{33}} = false$), it falls into deadlock (Nil) when it runs. According to transition rule 5, the following deductive formulas can be obtained for $W_{33} \parallel_{\{extending\}} CP$:

$$\begin{aligned}
&W_{33} \parallel_{\{extending\}} CP \\
&= ((run, false, 0, 161, 0.754) \\
&\quad \cdot(measure, false, 0, 161, 0.754) \\
&\quad \cdot(extending, false, 0, 161, 0.754).W_{33} \parallel_{\{extending\}} \\
&\quad \cdot((extending, true, 1, 0, 0).(extended, I_{CP}, r, T, r'_{CP}). \\
&\quad (idle_{CP}, I_{CP}, r, T, r'_{CP}).CP) \\
&= (run, false, 0, 161, 0.754) \\
&\quad \cdot((measure, false, 0, 161, 0.754) \\
&\quad \cdot(extending, false, 0, 161, 0.754).W_{33}) \parallel_{\{extending\}} \\
&\quad ((extending, true, 1, 0, 0).(extended, I_{CP}, r, T, r'_{CP}). \\
&\quad (idle_{CP}, I_{CP}, r, T, r'_{CP}).CP) \\
&= \text{Nil}
\end{aligned}$$

Namely,

$$W_{33} \parallel_{\{extending\}} CP = \text{Nil} \tag{27}$$

Using formula (27) and transition rule 5, the OCM can be simplified as follows.

$$\begin{aligned}
OCM = &((W_1 \parallel W_2 \parallel ((W_{311} \parallel W_{312}) + W_{32}) \parallel W_4 \parallel W_5 \parallel \\
&\times (W_{61} + W_{62}) \parallel W_7) \parallel_{\{extending\}} CP \\
&\parallel_{\{transfer\}} DB + \text{Nil})/H
\end{aligned} \tag{28}$$

TABLE 8. The component values of the activities in printing manufacturing modules.

Component	Printing manufacturing module									
	W_1	W_2	W_{31}	W_{32}	W_{33}	W_4	W_5	W_{61}	W_{62}	W_7
I_W	$true$	$true$	$true$	$true$	$false$	$true$	$true$	$true$	$true$	$true$
r	1	1	1	1	0	1	1	1	1	1
T_W/min	30	10	215	178	161	120	100	94	450	15
r'_W	1	1	0.662	0.731	0.762	1	1	0.830	0.344	1

Since the comprehensive evaluation probability $r'_{W_{31}}$ is less than $r'_{W_{32}}$, formula (28) can be simplified using transition rule 2.

$$OCM = ((W_1 \parallel W_2 \parallel W_{32} \parallel W_4 \parallel W_5 \parallel W_{61} \parallel W_7) \parallel_{\{extending\}} CP \parallel_{\{transfer\}} DB\big) /H \quad (29)$$

Since all activities belonging to set H ($extended$, $idle_{CP}$, $measure$, $idle_W$, $save$, $save$, $idle_{DB}$) are hidden, formula (29) can be expanded using Table 8, Definition 4 and transition rules 1 and 3 as follows.

$$\begin{aligned} &OCM \\ &= \left(run, I_{W_1}, r_{W_1}, T_{W_1}, r'_{W_1}\right) . \left(run, I_{W_2}, r_{W_2}, T_{W_2}, r'_{W_2}\right) \\ &\quad . \left(run, I_{W_{32}}, r_{W_{32}}, T_{W_{32}}, r'_{W_{32}}\right) . \left(run, I_{W_4}, r_{W_4}, T_{W_4}, r'_{W_4}\right) \\ &\quad . \left(run, I_{W_5}, r_{W_5}, T_{W_5}, r'_{W_5}\right) . \left(run, I_{W_{61}}, r_{W_{61}}, T_{W_{61}}, r'_{W_{61}}\right) \\ &\quad . \left(run, I_{W_7}, r_{W_7}, T_{W_7}, r'_{W_7}\right) . \left(completed, I_{CP}, r, T_{CP}, r'_{CP}\right) \\ &\quad . ((W_1 \parallel W_2 \parallel W_{32} \parallel W_4 \parallel W_5 \parallel W_{61} \parallel W_7) \parallel_{\{extending\}} \\ &\quad CP \parallel_{\{transfer\}} DB\big) /H \\ &= (run, true, 1, 30, 1) . (run, true, 1, 10, 1) \\ &\quad \cdot (run, true, 1, 178, 0.731) . (run, true, 1, 120, 1) \\ &\quad . (run, true, 1, 100, 1) . (run, true, 1, 94, 0.830) \\ &\quad . (run, true, 1, 10, 1) . (completed, true, 1, 542, 1) \\ &\quad . ((W_1 \parallel W_2 \parallel W_{32} \parallel W_4 \parallel W_5 \parallel W_{61} \parallel W_7) \parallel_{\{extending\}} \\ &\quad CP \parallel_{\{transfer\}} DB\big) /H \end{aligned} \quad (30)$$

Based on the recursive definition and rule 4, the OCM can be obtained using formulas (25) and (30).

$$\begin{aligned} &OCM \\ &= \left(run, I_{W_1}, r_{W_1}, T_{W_1}, r'_{W_1}\right) . \left(run, I_{W_2}, r_{W_2}, T_{W_2}, r'_{W_2}\right) \\ &\quad . \left(run, I_{W_{32}}, r_{W_{32}}, T_{W_{32}}, r'_{W_{32}}\right) . \left(run, I_{W_4}, r_{W_4}, T_{W_4}, r'_{W_4}\right) \\ &\quad . \left(run, I_{W_5}, r_{W_5}, T_{W_5}, r'_{W_5}\right) . \left(run, I_{W_{61}}, r_{W_{61}}, T_{W_{61}}, r'_{W_{61}}\right) \\ &\quad \cdot \left(run, I_{W_7}, r_{W_7}, T_{W_7}, r'_{W_7}\right) \\ &\quad \cdot \left(completed, I_{CP}, r, T_{CP}, r'_{CP}\right) .OCM \end{aligned} \quad (31)$$

It can be known from formula (31) that the optimal printing scheme is W_1, W_2, W_{32}, W_4, W_5, W_{61}, W_7, and its processing time T_{CP} is 542 minutes. From the operating principle of the OCM, we can conclude that the optimal printing scheme is selected for each manufacturing stage, and then the whole optimal printing scheme is constructed. This method is more efficient and time-saving than the one by one comparison of the reconfiguration scheme. In the printing stage, the OCM chose the rotary inkjet digital printer W_{32}, which has the characteristics of good printing quality, high efficiency and suitability for small-batch book production. Compared with the other two printing modes, the Océ JetStream digital inkjet color printer W_{33} is under maintenance, which makes that it unable to be used for production. The offset printing mode ($W_{311} \| W_{312}$) is not suitable for small-batch book printing (less than 2000 books) because the number of plate replacements is so high that the ramp-up time is longer and the costs increase. In the post-printing stage, compared with the thread sewing machine W_{62}, the binding machine W_{61} has the advantages of high efficiency and low costs. In summary, the selection of the optimal printing scheme meets expectations.

In addition, it can also be obtained from formula (31) that the OCM of the RPMS possesses the required external behavior, and $I_{CP} = true$ indicates that the optimal printing scheme has good integrity.

VI. CONCLUSION AND FUTURE WORK

Since the RPMS must be reconfigured according to the printing order changes, there are a variety of feasible reconfiguration schemes. In this paper, taking the RPMS as the research object, we study the optimal printing scheme and its integrity.

First, a comprehensive evaluation method considering both subjective and objective evaluations is proposed in this paper. The probability algorithms of the subjective and objective evaluations are designed by analyzing the printing process characteristics of the RPMS. Then, SPA is conservatively extended, and the OCM is established to describe the operation transition process of the RPMS. Using the SPA syntax, the OCM extends the integrity attribute, the integrity measurement probability and the comprehensive evaluation probability. The transition rules of the OCM are defined. The semantic model of the operation chain is constructed. Finally, we carry out experiments using an enterprise RPMS. The experimental results show that the optimal printing scheme meets expectations. The integrity measurement result

$I_{CP} = true$ shows that the optimal printing scheme has good integrity.

In the future, we will apply digital twin technologies to build a printing simulation workshop for printing enterprises and use advanced modeling and simulation tools to establish every link of the RPMS. More accurate processing times can be obtained by simulating printing processes.

REFERENCES

[1] J. Zhang, G. Frey, A. Al-Ahmari, T. Qu, N. Wu, and Z. Li, "Analysis and control of dynamic reconfiguration processes of manufacturing systems," *IEEE Access*, vol. 6, pp. 28028–28040, 2017.

[2] H. Li, R. Luo, S. Zhou, and S. Gao, "Research on reconfigurable mechanism of manufacturing system for printing process based on ACP," *Math. Problems Eng.*, vol. 2018, Jun. 2018, Art. no. 2323746.

[3] R. Luo, S. Gao, H. Li, and S. Zhou, "Modeling and verification of reconfigurable printing system based on process algebra," *Math. Problems Eng.*, vol. 2018, Oct. 2018, Art. no. 9189836.

[4] J. Hillston, *A Compositional Approach to Performance Modelling*. Cambridge, U.K.: Cambridge Univ. Press, 1996.

[5] M. Bernardo and R. Gorrieri, "A tutorial on EMPA: A theory of concurrent processes with nondeterminism, priorities, probabilities and time," *Theor. Comput. Sci.*, vol. 202, nos. 1–2, pp. 1–54, Jul. 1998.

[6] U. Herzog and M. Rettelbach, "TIPP—A language for timed processes and performance evaluation," Univ. Erlangen-Nürnberg, Birlian, Germany, Tech. Rep. 4/92, Nov. 1992.

[7] J. Hillston, "Fluid flow approximation of PEPA models," in *Proc. Int. Conf. Quant. Eval. Syst.*, Sep. 2005, pp. 33–42.

[8] M. Tribastone, S. Gilmore, and J. Hillston, "Scalable differential analysis of process algebra models," *IEEE Trans. Softw. Eng.*, vol. 38, no. 1, pp. 205–219, Jan./Feb. 2012.

[9] R. A. Hayden, "Scalable performance analysis of massively parallel stochastic systems," Ph.D. dissertation, Imperial College, London, U.K., 2011.

[10] M. Tribastone, J. Ding, S. Gilmore, and J. Hillston, "Fluid rewards for a stochastic process algebra," *IEEE Trans. Softw. Eng.*, vol. 38, no. 4, pp. 861–874, Jul./Aug. 2012.

[11] S. Srivastava and I. Banicescu, "Robust resource allocations through performance modeling with stochastic process algebra," *Concurrency Comput., Pract. Exper.*, vol. 29, no. 7, p. e3894, 2016.

[12] J. Ding, X.-S. Zhu, and X. Chen, "State equations in stochastic process algebra models," *IEEE Access*, vol. 7, pp. 61195–61203, 2019.

[13] T. M. Pinkston, R. Pang, and J. Duato, "Deadlock-free dynamic reconfiguration schemes for increased network dependability," *IEEE Trans. Parallel Distrib. Syst.*, vol. 14, no. 8, pp. 780–794, Aug. 2003.

[14] A. Robles-Gomez, A. Bermudez, and R. Casado, "A deadlock-free dynamic reconfiguration scheme for source routing networks using close up*/down* graphs," *IEEE Trans. Parallel Distrib. Syst.*, vol. 22, no. 10, pp. 1641–1652, Oct. 2011.

[15] F. Chen, Q. Wu, B. Jiang, and G. Tao, "A reconfiguration scheme for quadrotor helicopter via simple adaptive control and quantum logic," *IEEE Trans. Ind. Electron.*, vol. 62, no. 7, pp. 4328–4335, Jul. 2015.

[16] G. X. Wang, S. H. Huang, Y. Yan, and J. J. Du, "Reconfiguration schemes evaluation based on preference ranking of key characteristics of reconfigurable manufacturing systems," *Int. J. Adv. Manuf. Technol.*, vol. 89, pp. 2231–2249, Mar. 2017.

[17] Y. Li, Z. Sun, L. Han, and N. Mei, "Fuzzy comprehensive evaluation method for energy management systems based on an Internet of Things," *IEEE Access*, vol. 5, pp. 21312–21322, 2017.

[18] X. Wei, X. Luo, Q. Li, J. Zhang, and Z. Xu, "Online comment-based hotel quality automatic assessment using improved fuzzy comprehensive evaluation and fuzzy cognitive map," *IEEE Trans. Fuzzy Syst.*, vol. 23, no. 1, pp. 72–84, Feb. 2015.

[19] D. Li, W. Wang, Q. Li, and J. Cheng, "A comprehensive evaluation of scheduling methods of virtual machine migration for energy conservation," *IEEE Syst. J.*, vol. 11, no. 2, pp. 898–909, Jun. 2017.

[20] Z. A. Siddiqui and K. Tyagi, "Study on service selection effort estimation in service oriented architecture-based applications powered by information entropy weight fuzzy comprehensive evaluation model," *IET Softw.*, vol. 12, no. 2, pp. 76–84, Apr. 2018.

[21] C. A. R. Hoare, "Communicating sequential processes," *Commun. ACM*, vol. 21, no. 8, pp. 666–677, 1978.

[22] R. Milner, *A Calculus of Communicating Systems*. New York, NY, USA: Springer-Verlag, 1982.

[23] W. Fokkink, *Introduction to Process Algebra* (Computer Science-Monograph), 2nd ed. Berlin, Germany: Springer-Verlag, 2007.

[24] Y. Zhang, Y. Chen, and H. Wu, "A process algebra with qualitative calculus for modeling spatio-temporal behaviour," *IEEE Access*, vol. 7, pp. 57172–57187, 2019.

[25] J. Hillston, H. Hermanns, U. Herzog, V. Mertsiotakis, and M. Rettelbach, "Stochastic process algebras: Integrating qualitative and quantitative modelling," in *Formal Description Techniques VII*. New York, NY, USA: Springer, 1995.

HUAILIN LI received the M.S. degree in light industry technology and engineering from the Xi'an University of Technology, Xi'an, China, in 2015, where he is currently pursuing the Ph.D. degree. His research interests include performance modeling and evaluation for printing manufacturing systems and printing process control.

SHISHENG ZHOU received the Ph.D. degree in biomedical engineering from Xi'an Jiaotong University, Xi'an, China, in 1996. He is currently a Professor with the Faculty of Printing, Packaging Engineering and Digital Media Technology, Xi'an University of Technology, Xi'an. He is also the Chairman of the Shaanxi Collaborative Innovation Center of Green Intelligent Printing and Packaging and the Chairman of Shaanxi Provincial Key Laboratory of Printing and Packaging Engineering, Xi'an. His research interests include color information and science, and intelligent printing manufacturing systems.

RUBAI LUO received the M.S. degree and the Ph.D. degree in mechanical engineering from the Xi'an University of Technology, Xi'an, China, in 2007 and 2010, respectively, where he is currently an Associate Professor with the Faculty of Printing, Packaging Engineering and Digital Media Technology. His research interests include intelligent printing manufacturing systems and printing electronic materials.

BIN DU received the M.S. degree and the Ph.D. degree in mechanical engineering from the Xi'an University of Technology, Xi'an, China, in 2010 and 2016, respectively. He is currently an Associate Professor with the Shaanxi Collaborative Innovation Center of Green Intelligent Printing and Packaging, Xi'an. His research interests include printing electronic materials and printing manufacturing systems.