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Research Article

Research on Reconfigurable Mechanism of Manufacturing System for Printing Process Based on ACP

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The reconfiguration manufacturing system (RMS) allows mass manufacturing to be changed into customized mass production and short-series production. However, the existing RMS models are not applicable to the printing production process, which is coexistence of the hybrid nature of being continuous and discrete. With the printing manufacturing system as the object of the research, this paper proposes the Agent-Resource-Workstation (ARW) model based on agent by analyzing the characteristics of "Production and Consumption of Resources" in the printing process. And then, each component of the ARW model is analyzed and defined. Finally, after systematically abstracting the reconfiguration of workstation models (RWMs), the reconfigurable mechanism of RWMs is established based on the algebra of communicating process (ACP), and formal verification was conducted by applying axioms of process algebra. The verification results show that RWM can show its external behavior well. Meanwhile, our research provides a theoretical approach for the reconfiguration of the printing manufacturing system.

1. Instruction

At present, the direction of international advanced printing manufacturing system is going gradually to digital network and intelligence. Reconfigurable printing manufacturing system (RPMS) provides the best way to do this. In the late 1990s, Y. Koren, the professor of University of Michigan, proposed the concept of reconfigurable manufacturing system [1]. The model and design theory of reconfigurable systems mostly focused on the discrete manufacturing system, which is typical of machining. Because function block model is regarded as the key to improve the efficiency of reconstruction, we abstract model from the function block of system before reconstructing the printing manufacturing system, and then the model is formally verified. Finally, the reconfigurable principle of the manufacturing system is explored.

Recently, agent-based function block and IEC 61499-based function block are proposed for the RMS. Mulibika and Basson [2], as well as Kruger and Basson [3], have compared these two approaches. Although Valentea, Mazzolinib, and Carpanzanoa [4] have confirmed that IEC 61499 holds promise for RMS applications, there has been a severe lack of support for this standard by major automation controller vendors, and the development platforms to support this approach are not mature enough to be attractive to the industry. IEC 61499 further does not make provision for dynamic instantiation, which inhibits its ability to implement holonic control architectures [5]. However, most research in RMS has used the agent-based system, such as referred to in [6–13]. A. Maka et al. have used agent-based modeling in modeling decision-making systems, which allows more flexibility than standard central management systems [6]. The use of agent-based systems allows mass manufacturing to be changed into customized mass production and short-series production, as recently confirmed by R Cupek et al. [7]. The most important properties of an agent are the autonomy, intelligence, adaptation, and cooperation [11].

Nevertheless, most research assumes that the agent in the manufacturing execution system can understand the interactive message and the perceptual environment and can

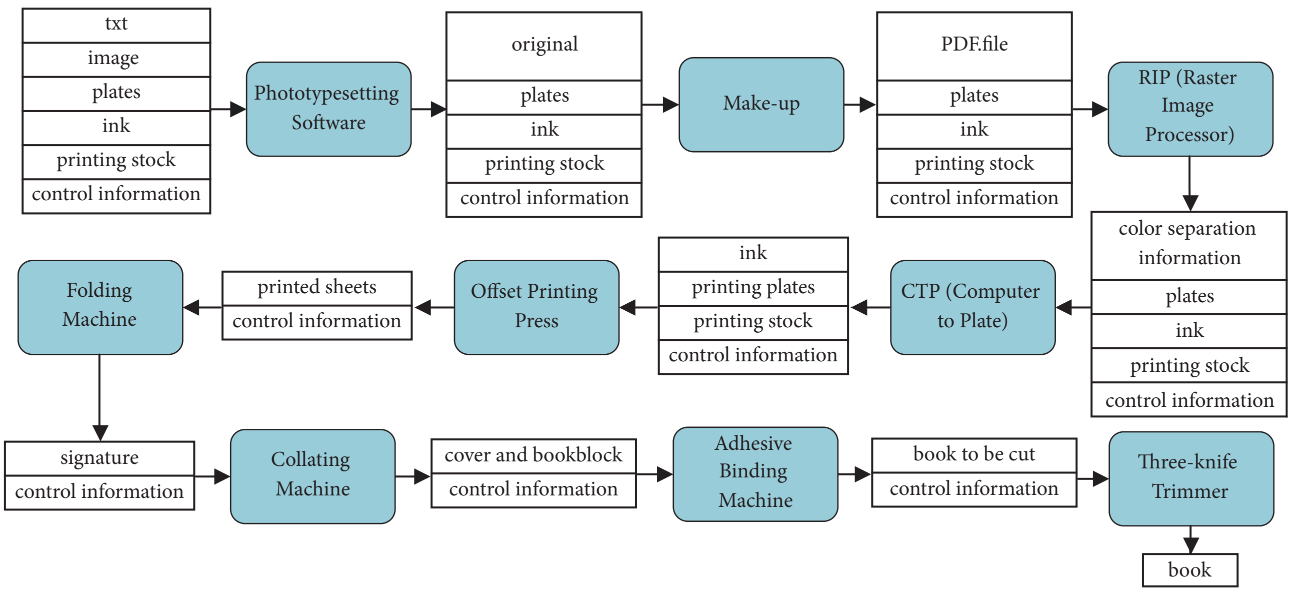

Figure 1: The printing process of a book.

be reconstructed spontaneously by reasoning. This approach has a high demand for the agent reasoning ability, and it is difficult to realize this technology. Since there is no corresponding reconfigurable mode guidance, so that a large number of interactions between agents exist and the reconfigurable efficiency of system are low. An ARC-model-based (Agent model, Role model, and Characteristic model) method for realizing this kind of reconfiguration and a corresponding ARMES prototype were proposed by National CIMS Engineering Research Center, Tsinghua University [12]. The data structure based on the ARC model is not adapted to the data structure in the RPMS based on the "Production and Consumption of Resources" production process model. If we apply reconfigurable theory based on ARC model to guide the reconfiguration of printing manufacturing system, the coupling between the information flow and the control system of the system is enhanced, and the reconfiguration efficiency is reduced. Therefore, On the basis of studying the influence mechanism of structured control information data on RPMS, a new reconfigurable theory based on Agent-Resource-Workstation (ARW) model is proposed in this paper.

When manufacturing systems are reconfigurable, A. Youssef proposed that the maximum investment constraints of configurations and the space constraints should be satisfied [13, 14]. Lou Hongliang et al. used Graph Theory to research on the reconstruction strategy of RMS full-life cycle under the variety and batch changes of parts [15]. Under the deterministic market demand environment, Duan Jianguo et al. discussed that production drives the reconfiguration method of the RMS [16]. All of the research [13–16] is independent of the control quantity, and the discrete machining system is the object of study. Dai Yuru and Wang Jian have used the Component Hybrid Petri net method to reconfigure manufacturing modeling for continuous chlorine production system [17]. However, these models are not applicable to the printing production process, which is coexistence of the hybrid nature of continuous and discrete. Since the process algebra [18] has precise formal semantics and rigorous mathematical foundation, the subsystem can be combined into a large system by operator, and the system actions can be hidden as an internal activity by hiding the operator, and the model can be formal verification based on the algebraic axioms. Currently, the process algebra is more used in the field of software communications and less applied in the reconfigurable manufacturing system [19]. Based on the ARW component model, this paper utilizes process algebra to abstract the attributes and behavior characteristics of reconfigurable system. Furthermore, the algebraic model of RWMs is established, and then the formal verification of model is carried out.

2. Proposed ARW Model

Figure 1 shows us the printing process of a book. It is easy to see that the essence of the printing production manufacture is a constant process, in which old resources (raw materials) are consumed and then new resources are produced. When applying the "Production and Consumption of Resources" model to define the printing production manufacture process, we can regard each production process as a workstation of processing resource. Resources are consumed to manufacture new resources, which are used by the subsequent workstation. Thus, the workflow is constituted. The resources are defined as the various types of information resources (such as various agreements, rules, and control information) and as entity resources (such as paper, ink, and printing equipment) in the workflow. For example, with the control information, text and images are designed into original, which is consumed to manufacture the PDF file by the Made-up (such as Adobe InDesign, CorelDRAW, and FanTart), as shown in Figure 1. Therefore, the Agent-Resource-Workstation (ARW) model is proposed based on the functions, attributes, and behaviors

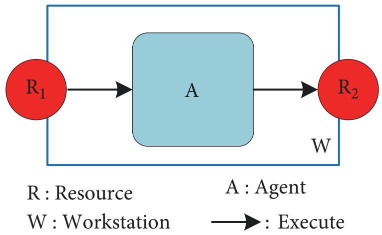

FIGURE 2: ARW model.

of the manufacturing units. The ARW model is composed of Agent model, Resource model, and Workstation model, as shown in Figure 2.

3. Reconfiguration of the Workstation Model

In the ARW model, the Agent model is defined as a component kernel, which depicts the processing functions and the structure of the Agent type. The Agent model is expressed by internal processing functions. The Resource model is a set of various resources. The attributes of resource include the resource type, the interaction of the materials, and the behavior constraints of the manufacturing suitability. The Agent model and the Resource model are integrated in Workstation model, which is expressed by interface and behavior. The Resource model is an interface of the Workstation model. The interface is a poset (Partially Ordered Set) that depicts the coupling relationship between the resources. The behavior consists of an internal processing functions' set which depicts the execution relationship between the Agent model and the Resource model, the interface element of the interactive protocol, and a set of messages received and sent. When the Agent model executes the Resource model, it means that the Agent model promises to implement the service functions and the production behaviors (Production and Consumption of Resources) of the Resource model defined. The Agent model complexes with the others to integrate into a new Workstation only through the interface (Resource model). The reconfigurable principle of Workstation models based on the ARW model is shown in Figure 3. Since the output resources of W_1 are the same as the input resources of W_2 (W_3) in Figure 3, namely, interface matching, W_1 and W_2 (W_3) can be reconfigured. This is a reconfigurable type called *additional reconfiguration*. Another type is *replaceable reconfiguration*. Due to the production process changing, W_2 has to be replaced by W_3 and then reconstructed with W_1. For example, in the production of a book, saddle stitches are required when signatures are no more than six. The adhesive binding machine in Figure 1 just needs to be replaced into the saddle stitching machine. W_1 and W_4 cannot be reconfigured, because the output resources of W_1 are different from the input resources of W_4, namely, interface mismatching.

The Workstation model can be reconfigured with another Workstation model or more Workstation models by additional reconfiguration. Depending on the different dimensions of the integration, the new Workstation model will contain two or more component kernels, as shown in Figure 4.

4. Mathematical Model

To specify more complex systems, the algebra of communicating process (ACP) [20] specification framework offers constants, operators, recursion, etc. as follows:

(1) A constant δ is called *deadlock*, which does not display any behavior, and the other constant τ is called the *silent step*, which represents a sequence of internal actions that can be eliminated from a process graph.

(2) A unary operator ∂_H is called *encapsulation* for sets H of atomic actions, which rename all actions in H into δ. And the other unary operator τ_I is called *abstraction* for sets I of atomic actions, which rename all actions in I into τ.

(3) The binary operators $(+)$, $(\cdot)$, $(\|)$, $(\lfloor\!\lfloor)$, and $(|)$ are called the *alternative*, *sequential*, *merge*, *left merge*, and *communication merge composition* operators, respectively. The three parallel operators $(\|)$, $(\lfloor\!\lfloor)$, and $(|)$ bind stronger than $(+)$ and $(\cdot)$.

If E is a *guarded recursive specification* and X is called *recursion variable* in E, then $\langle X \mid E\rangle$ is called *guarded linear recursion*, which intuitively denotes the process that has to be substituted for X in the solution for E.

Resource elements $d_1, d_2, d_3, \cdots$ from a finite set Δ are initial input resources (R_1). Resource elements $d'_1, d'_2, d'_3, \cdots$ from a finite set Δ' are the output resources (R_2) of the Workstation one (W_1), and they are also the input resources of the Workstation two (W_2). Resource elements $d''_1, d''_2, d''_3, \cdots$ from a finite set Δ'' are the output resources (R_3) of A_2.

First, as shown in Figure 5, W_1 reads a resource d from channel A, then this resource d is consumed to produce resource d' by the agent of the W_1. Second, the W_1 sends the resource d' into the channel B. However, when the resource d' is lost or the channel B is corrupted, so that the resource d' that cannot be received by the W_2 can be turned into an error message $\perp$, which is sent into the channel B. Thirdly, the W_2 receives the resource d' or the error message $\perp$ via channel B. If the W_2 receives the error message $\perp$ or the resource d' that cannot be manufactured by the agent of the W_2, then it sends the acknowledgement message $\perp$ or $\perp_{d'}$ into the channel D. The W_1 will send the (right) resource d' into the channel B again when it receives the acknowledgement message $\perp$ or $\perp_{d'}$. If the agent of the W_2 can use the resource d' to produce the resource d'', the W_2 sends the resource d'' into channel C. Finally, the W_2 sends the acknowledgement message O to the W_1 via the channel D.

Applying ACP, we can describe the states of the W_1:

$$\begin{aligned} S &= \sum_{d\in\Delta} r_A(d)\cdot T \\ T &= \left(s_B(\perp) + s_B\left(d'\right)\right)\cdot U \\ U &= r_D(O)\cdot S + \left(r_D(\perp) + r_D\left(\perp_{d'}\right)\right)\cdot T. \end{aligned} \tag{1}$$

Applying ACP, we can describe the states of the W_2:

$$R = \sum_{d'\in\Delta'} \sum_{d''\in\Delta''} \left\{ r_B\left(d'\right) s_c\left(d''\right)\cdot P + r_B(\perp)\cdot Q\right.$$

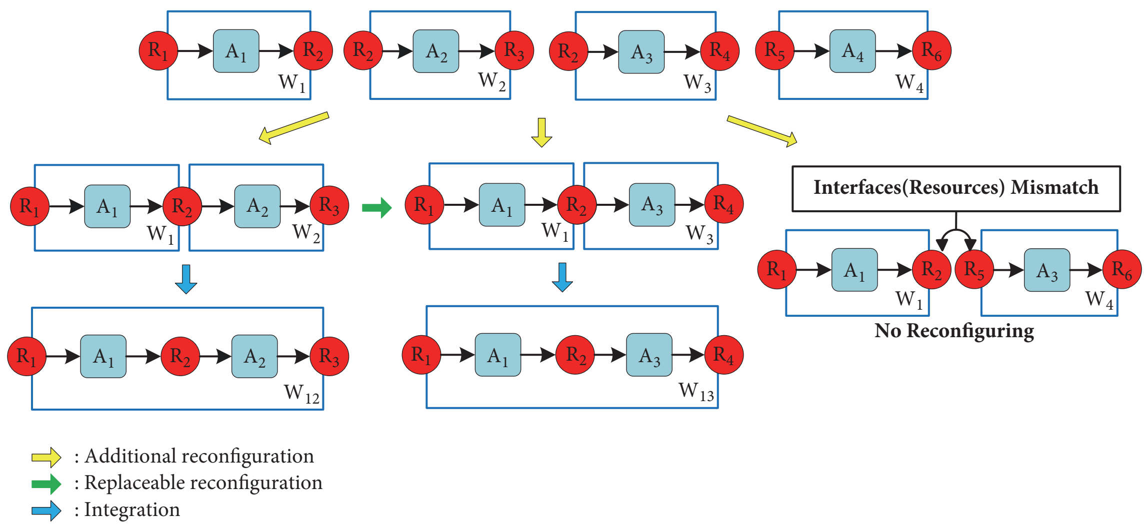

FIGURE 3: Reconfigurable principle of Workstation models based on ARW model.

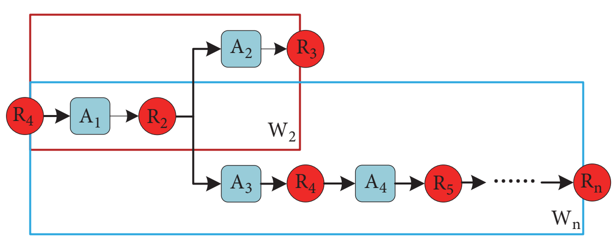

FIGURE 4: Different dimensions of the integration for Workstation models.

$$
\begin{aligned}
&+ r_B\left(d'\right) s_D\left(\perp_{d'}\right) \cdot R\Big\} \\
Q &= s_D(\perp) \cdot R \\
P &= s_D(\mathrm{O}) \cdot R.
\end{aligned} \tag{2}
$$

A send and a read action of the message $(d', \perp_{d'}, \perp$ *or* $\mathrm{O})$ over the same channel (B or D) communicate with each other:

$$
\begin{aligned}
\gamma\left(s_B\left(d'\right), r_B\left(d'\right)\right) &\triangleq c_B\left(d'\right) \\
\gamma\left(s_B(\perp), r_B(\perp)\right) &\triangleq c_B(\perp) \\
\gamma\left(s_D\left(d'\right), r_D\left(d'\right)\right) &\triangleq c_D\left(d'\right) \\
\gamma\left(s_D(\perp), r_D(\perp)\right) &\triangleq c_D(\perp) \\
\gamma\left(s_D\left(\perp_{d'}\right), r_D\left(\perp_{d'}\right)\right) &\triangleq c_D\left(\perp_{d'}\right) \\
\gamma\left(s_D(\mathrm{O}), r_D(\mathrm{O})\right) &\triangleq c_D(\mathrm{O})
\end{aligned} \tag{3}
$$

for $d' \in \Delta'$. All other communications between atomic actions result in δ.

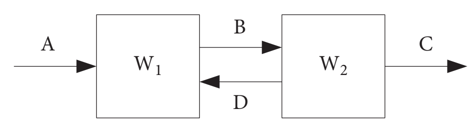

FIGURE 5: Abstract of RWMs.

5. Formal Verification

The desired concurrent system is obtained by putting S and R in parallel, encapsulating *send* and *read* actions over the internal channels B and D, and abstracting away from communication actions over these channels. That is, the RWMs are expressed by the process term

$$\tau_I \partial_H (S \parallel R) \tag{4}$$

with

$$
\begin{aligned}
H &= \left\{s_B\left(d'\right), r_B\left(d'\right), s_D\left(d'\right), r_D\left(d'\right) \mid d' \in \Delta'\right\} \\
&\quad \cup \left\{s_B(\perp), r_B(\perp), s_D(\perp), r_D(\perp), s_D(\mathrm{O}), r_D(\mathrm{O})\right\} \\
I &= \left\{c_B\left(d'\right), c_D\left(d'\right) \mid d' \in \Delta'\right\} \\
&\quad \cup \left\{c_B(\perp), c_D(\perp), c_D(\mathrm{O})\right\}.
\end{aligned} \tag{5}
$$

The process term $S \parallel R$ can be expanded by using axioms of process algebra as follows:

$$
\begin{aligned}
S \parallel R = &\sum_{d \in \Delta} r_A(d) \cdot (T \parallel R) \\
&+ \sum_{d' \in \Delta'} \sum_{d'' \in \Delta''} r_B\left(d'\right)\left(s_c\left(d''\right) P \parallel S\right) \\
&+ r_B(\perp)(Q \parallel S) \\
&+ \sum_{d' \in \Delta'} r_B\left(d'\right)\left(\left(s_D\left(\perp_{d'}\right) R\right) \parallel S\right)
\end{aligned} \tag{6}
$$

Applying unary encapsulation operator ∂_H, (6) can be encapsulated and reduced. We can derive

$$\partial_H (S \parallel R) = \sum_{d\in\Delta} r_A(d) \cdot \partial_H (T \parallel R). \tag{7}$$

Similarly, these derivations are sketched as follows:

(I) $\partial_H (S \parallel R) = \sum_{d\in\Delta} r_A(d) \cdot \partial_H (T \parallel R)$

$$\begin{aligned}
&\text{(II)}\ \partial_H (T \parallel R) \\
&\quad = \sum_{d'\in\Delta'} \sum_{d''\in\Delta''} c_B(d')\, \partial_H (U \parallel (s_c(d'') \cdot P)) \\
&\qquad + c_B(\perp)\, \partial_H (U \parallel Q) \\
&\qquad + \sum_{d'\in\Delta'} c_B(d')\, (U \parallel (s_D(\perp_{d'}) \cdot R))
\end{aligned} \tag{8}$$

(III) $\partial_H (U \parallel (s_c(d'') \cdot P)) = s_c(d'')\, \partial_H (U \parallel P)$

(IV) $\partial_H (U \parallel Q) = c_D(\perp)\, \partial_H (T \parallel R)$

(V) $\partial_H (U \parallel (s_D(\perp_{d'}) \cdot R)) = c_D(\perp_{d'})\, \partial_H (T \parallel R)$

(VI) $\partial_H (U \parallel P) = c_D(O)\, \partial_H (S \parallel R)$.

The recursive specification E of the RWMs, consisting of the recursive equations for the recursion variables S, T, U, R, Q, and P, can be transformed into linear form by introducing extra recursion variables to represent $s_c(d'') \cdot Q$ for $d'' \in \Delta''$. For notational convenience, process terms $\langle X \mid E\rangle$ are abbreviated to X in this section. Owing to (I)-(VI), RSP yields

$$\partial_H (S \parallel R) = \langle X_1 \mid E\rangle \tag{9}$$

where E denotes the linear recursive specification

$$\begin{aligned}
X_1 &= \sum_{d\in\Delta} r_A(d) \cdot X_2 \\
X_2 &= \sum_{d'\in\Delta'} \sum_{d''\in\Delta''} c_B(d') \cdot X_3 + c_B(\perp) \cdot X_4 \\
&\quad + \sum_{d'\in\Delta'} c_B(d') \cdot X_5 \\
X_3 &= s_c(d'')\, X_6 \\
X_4 &= c_D(\perp) \cdot X_2 \\
X_5 &= c_D(\perp_{d'}) \cdot X_2 \\
X_6 &= c_D(O) \cdot X_1.
\end{aligned} \tag{10}$$

After application of the abstraction operator τ_I to the process term $\langle X_1 \mid E\rangle$, the loops of communication actions (between recursion variables X_2 and X_4, X_2, and X_5) become τ-loops, which can be eliminated by using CFAR.

$$\sum_{d\in\Delta} r_A(d)\, \tau_I \langle X_2 \mid E\rangle = \sum_{d\in\Delta} r_A(d)\, \tau_I \langle X_3 \mid E\rangle \tag{11}$$

Applying axioms of process algebra and (11) we can derive

$$\begin{aligned}
\tau_I (\langle X_1 \mid E\rangle) &= \sum_{d\in\Delta} r_A(d)\, \tau_I \langle X_3 \mid E\rangle \\
&= \sum_{d\in\Delta} \sum_{d''\in\Delta''} r_A(d)\, s_c(d'')\, \tau_I \langle X_1 \mid E\rangle
\end{aligned} \tag{12}$$

In combination with (9) this yields

$$\begin{aligned}
&\tau_I (\partial_H (S \parallel R)) \\
&\quad = \sum_{d\in\Delta} \sum_{d''\in\Delta''} r_A(d)\, s_c(d'')\, \tau_I (\partial_H (S \parallel R))
\end{aligned} \tag{13}$$

Equation (13) shows that the desired concurrent system can successfully read the resources d and manufacture the resources d'' to send it. It means that the RWMs exhibit the desired external behavior. The formal verification of the RWMs is finished.

The reconfiguration of the manufacturing system must meet the conditions of interface matching. It means that, in the reconfigurable printing manufacturing system, the output resources of each workstation must be produced by the subsequent workstation. Formal verification results show that the RWMs can realize the reconfiguration of the printing manufacturing system.

6. Conclusions

In this paper, reconfigurable mechanism of manufacturing system for printing process based on ACP is presented and studied. In the fast-varying production environment, the target of the printing manufacturing system can make the best printing process in time according to the technological requirements of product. The following work is mainly completed: Firstly, by analyzing the characteristics of "production and consumption of resources" in the printing process, this paper proposes the ARW model based on agent with the printing manufacturing system as the object of the research. Secondly, each component of the ARW model is analyzed and defined through the analysis of the printing equipment and materials. Finally, the reconfigurable mechanism of the RWMs is established based on ACP after systematically abstracting the RWMs, and formal verification was conducted by using axioms of process algebra. The verification results show that the RWMs can display its external behavior well. Meanwhile, the reconfigurable mechanism of the printing manufacturing system is sufficiently stable for the rapid change in the printing process.

Appendix

A. Axioms for BPA

A1 $x + y = y + x$;

A2 $(x + y) + z = x + (y + z)$;

A3 $x + x = x$;

A4 $(x + y) \cdot z = x \cdot z + y \cdot z$;

A5 $(x \cdot y) \cdot z = x \cdot (y \cdot z)$.

B. Axioms for PAP

M1 $x \parallel y = (x ⫫ y + y ⫫ x) + x \mid y$;

LM2 $v ⫫ y = v \cdot y$;

LM3 $v \cdot x ⫫ y = v \cdot (x \parallel y)$;

LM4 $(x + y) ⫫ z = x ⫫ z + y ⫫ z$;

CM5 $v \mid w = \gamma(v, w)$;

CM6 $v \mid (w \cdot y) = \gamma(v, w) \cdot y$;

CM7 $(v \cdot x) \mid w = \gamma(v, w) \cdot x$;

CM8 $(v \cdot x) \mid (w \cdot y) = \gamma(v, w) \cdot (x \parallel y)$;

CM9 $(x + y) \mid z = x \mid z + x \mid z$;

CM10 $x \mid (y + z) = x \mid y + x \mid z$.

C. Axioms for ACP

A6 $x + \delta = x$;

A7 $\delta \cdot x = \delta$;

D1 $v \notin H\ \partial_H(v) = v$;

D2 $v \in H\ \partial_H(v) = \delta$;

D3 $\partial_H(\delta) = \delta$;

D4 $\partial_H(x + y) = \partial_H(x) + \partial_H(y)$;

D5 $\partial_H(x \cdot y) = \partial_H(x) \cdot \partial_H(y)$;

LM11 $\delta ⫫ x = \delta$;

CM12 $\delta \mid x = \delta$;

CM13 $x \mid \delta = \delta$.

D. Recursive Definition and Specification Principles

RDP $\langle X_i \mid E \rangle = (\langle X_1 \mid E \rangle, \cdots, \langle X_n \mid E \rangle)\ (i \in \{1, \cdots, n\})$;

RSP If $y_i = t_i(y_1 \cdots y_n)\ (i \in \{1, \cdots, n\})$, then $y_i = \langle X_i \mid E \rangle\ (i \in \{1, \cdots, n\})$.

E. Axioms for Projection Operators

PR1 $\pi_n(x + y) = \pi_n(x) + \pi_n(y)$;

PR2 $\pi_{n+1}(v) = v$;

PR3 $\pi_{n+1}(v \cdot x) = v \cdot \pi_n(x)$;

PR4 $\pi_0(x) = \delta$;

PR5 $\pi_n(\delta) = \delta$.

F. Approximation Induction Principle

AIP If $\pi_n(x) = \pi_n(y)\ \ for\ n \in \mathbb{N}, then\ x = y$.

G. Axioms for the Silent Step

B1 $v \cdot \tau = \tau$;

B2 $v \cdot (\tau \cdot (x + y) + x) = v \cdot (x + y)$.

H. Axioms for Abstraction Operators

TI1 $v \notin I\ \tau_I(v) = v$;

TI2 $v \in I\ \tau_I(v) = \tau$;

TI3 $\tau_I(\delta) = \delta$;

TI4 $\tau_I(x + y) = \tau_I(x) + \tau_I(y)$;

TI5 $\tau_I(x \cdot y) = \tau_I(x) \cdot \tau_I(y)$.

I. Cluster Fair Abstraction Rule

CFAR If X is in a cluster for I with exits

$\{v_1 Y_1, \cdots, v_m Y_m, w_1, \cdots, w_n\}, then$

$\tau \cdot \tau_I(\langle X \mid E \rangle) = \tau \cdot \tau_I(v_1 \langle Y_1 \mid E \rangle + \cdots + v_m \langle Y_m \mid E \rangle + w_1 + \cdots + w_n)$

Nomenclature

d:	Input resources of the W_1
d':	Output resources of the W_1 and input resources of the W_2
d'':	Output resources of the W_2
Δ:	A set of resources d
Δ':	A set of resources d'
Δ'':	A set of resources d''
$\perp_{d'}$:	The acknowledgement message that the resource d' cannot be processed by the agent of the W_2
$\perp$:	The error message
O:	The acknowledgement message that d' can be processed by the agent of the W_2
$r_A(d)$:	Read the resources d from the channel A
$r_B(d')$:	Read the resources d' from the channel B
$r_D(O)$:	Read the message O from the channel D
$r_B(\perp)$:	Read the message $\perp$ from the channel B
$r_D(\perp_{d'})$:	Read the message $\perp_{d'}$ from the channel D
$s_B(d')$:	Send the resources d' into the channel B
$s_C(d'')$:	Send the resources d' into the channel C
$s_D(O)$:	Send the message O into the channel D
$s_B(\perp)$:	Send the message $\perp$ into the channel B
$s_D(\perp_{d'})$:	Send the message $\perp_{d'}$ into the channel D
S:	The initial state of the W_1
T:	The state of successfully manufacturing resources d'
U:	The state of waiting the acknowledgement message
R:	The initial state of the W_2
Q:	The state of receiving the error message
P:	The state of successfully manufacturing resources d''.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

[1] Y. Koren, U. Heisel, F. Jovane et al., "Reconfigurable manufacturing systems," *CIRP Annals—Manufacturing Technology*, vol. 48, no. 2, pp. 527–540, 1999.

[2] C. Mulibika and A. H. Basson, "Comparison of IEC 61499 and agent based control for a reconfigurable manufacturing subsystem," in *Proceedings of the in COMA13, International Conference on Competitive Manufacturing*, D. Dimitrov and C. Schutte, Eds., pp. 283–288, Stellenbosch: Department of Industrial Engineering, Stellenbosch Universit, 2013.

[3] K. Kruger and A. H. Basson, "Multi-agent systems vs IEC 61499 for holonic resource control in reconfigurable systems," in *Proceedings of the 46th CIRP Conference on Manufacturing Systems, CIRP CMS 2013*, pp. 503–508, prt, May 2013.

[4] A. Valente, M. Mazzolini, and E. Carpanzano, "An approach to design and develop reconfigurable control software for highly automated production systems," *International Journal of Computer Integrated Manufacturing*, vol. 28, no. 3, pp. 321–336, 2015.

[5] A. J. Hoffman and A. H. Basson, "IEC 61131-3-based holonic control of a reconfigurable manufacturing subsystem," *International Journal of Computer Integrated Manufacturing*, vol. 29, no. 5, pp. 520–534, 2016.

[6] A. Maka, R. Cupek, and M. Wierzchanowski, "Agent-based modeling for warehouse logistics systems," in *Proceedings of the 2011 UKSim 13th International Conference on Modelling and Simulation, UKSim 2011*, pp. 151–155, April 2011.

[7] R. Cupek, A. Ziebinski, L. Huczala, and H. Erdogan, "Agent-based manufacturing execution systems for short-series production scheduling," *Computers in Industry*, vol. 82, pp. 245–258, 2016.

[8] M. Rolón and E. Martínez, "Agent-based modeling and simulation of an autonomic manufacturing execution system," *Computers in Industry*, vol. 63, no. 1, pp. 53–78, 2012.

[9] J. Gamboa-Revilla and M. Ramirez-Cadena, "Intelligent manufacturing systems: a methodology for technological migration," in *Proceedings of the World Congress on Engineering*, vol. 2, pp. 1257–1262, 2008.

[10] X. L. Xu and J. Q. Guan, "Research on the integrated multi-view modeling for RMS based on multi-agent," in *Proceedings of the International Conference on Electrical, Control and Automation Engineering*, pp. 343–347, December 2013.

[11] P. Leitão and F. Restivo, "ADACOR: a holonic architecture for agile and adaptive manufacturing control," *Computers in Industry*, vol. 57, no. 2, pp. 121–130, 2006.

[12] H. Zhou, M. Liu, and C. Wu, "Research on agent-based reconfigurable manufacturing execution systems," *Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS*, vol. 11, no. 6, pp. 776–780, 2005.

[13] A. M. A. Youssef and H. A. Elmaraghy, "Modelling and optimization of multiple-aspect RMS configurations," *International Journal of Production Research*, vol. 44, no. 22, pp. 4929–4958, 2006.

[14] A. M. Youssef and H. A. ElMaraghy, "Optimal configuration selection for reconfigurable manufacturing systems," *International Journal of Flexible Manufacturing Systems*, vol. 19, no. 2, pp. 67–106, 2007.

[15] H. Lou, "Reconfigurating policy of reconfigurable manufacturing systems based on graph theory," *Chinese Journal of Mechanical Engineering*, vol. 42, no. 03, pp. 22–28, 2006.

[16] J. Duan, A. Li, N. Xie, and L. Xu, "Reconfiguration method on production capacity expansion in RMS," *Tongji Daxue Xuebao/Journal of Tongji University*, vol. 40, no. 9, pp. 1357–1363, 2012.

[17] Y.-R. Dai and J. Wang, "Reconfigurable modeling approach for multi-coupling and hybrid process in the process industry," *Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS*, vol. 17, no. 11, pp. 2457–2466, 2011.

[18] R. Milner, *A Calculus of Communicating Systems*, Lecture Notes in Computer Science, Springer, New York, NY, USA, 1980.

[19] Y. Y. Wei, C. H. Lin, and L. Q. Tian, "Represent and analyze with adaptive workflow by process algebra," *Acta Electronica Sinica*, vol. 30, no. 11, pp. 1624–1628, November 2002.

[20] W. Fokkink, *Introduction to process algebra*, Computer Science–Monograph (English), Springer-Verlag, Berlin, 2nd edition, 2007.