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The Ant Colony Algorithm Based on Logic Time Petri Nets and Application in Electronic-Commerce Logistics

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ABSTRACT Based on Logic Time Petri nets (LTPNs) models, this paper focuses on improving the efficiency of Petri Net intelligent search method execution. With an analysis of the E-Commerce Logistics (ECL) system, the method of system scheduling using LTPNs is studied, and the Ant Colony algorithm is proposed based on it. By introducing the concept of pheromones to system transition, using the Ant Colony algorithm (ACA) in the processing of the network, and setting the heuristic factor in combination with the time boundary, the non-deterministic behavior can be automatically analyzed and selected in the LTPNs so that the efficiency of control and scheduling during the system dynamics operation is improved. The result of the analysis of the ECL system serves as evidence of the superiority of ACA.

INDEX TERMS Ant colony optimization, electronic-commerce logistics, logic time Petri nets.

I. INTRODUCTION

Based on Internet technology, E-Commerce Logistics (ECL) has developed rapidly in recent years. The ECL service system contains business flow, capital flow, information flow, and logistics, and has the general characteristics of a discrete event dynamic system. Compared with the previous logistics system, it is a more complex ERP (Enterprise Resource Planning) system. System scheduling is an urgent problem that remains to be solved [1].

As a logical tool, Petri Nets – a graphical modeling method for discrete parallel systems - is widely used in industrial environment modeling and scheduling. During model processing, the system's structure and dynamic behavior can both be defined [2]. Process control and system scheduling (which are both common and important in a real-world environment) can be end-to-end optimized, from initial identification to target identification, in Petri Net. Such optimization can then be modeled and processed.

Based on an existing application process, various extended Petri Net models are established to solve specific problems. For example, Logical Petri Nets are abstractions and extensions of arc Petri Nets and advanced Petri Nets. In LPNs (Logical Petri Nets) the transition input and output are limited by logical expressions and some new nets are generated by the extension of time, color, data, queue and other concepts on LPNs. Logical time network can simultaneously solve the problem of real-time restriction and the uncertainty value expression and, as a result, can describe the real-time collaborative working system better. Due to these characteristics, the logical time network serves as a strong option for this type of modeling and algorithm optimization. Colored Logic Petri Nets (CLPNs) can describe uncertain logical data output transformation. Logical Data Petri Nets (LDPNs) define the attributes of tokens and the arrival times at a location, thereby solving the problem of system priority in the handling of tokens. Queue Logical Petri Nets (QLPNs) describe the scheduling of the fair sharing system of resources, etc. [3]–[7].

The above is an analysis and recommendation for improvement of Petri Net's static modeling, with scheduling in dynamic operations handled primarily through the implementation of algorithms [8]–[10].

Algorithms can be combined with different types of Petri Nets – an approach which has been studied at length. One such example would be the use of improved Petri Net-based

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modeling of random Petri Net in flexible manufacturing systems and the use of fuzzy Petri Net in system behavior identification and fault diagnosis. But in ECL, the system's requirements for real-time and the passing value indeterminacies are cannot be met in the scheduling, so the efficiency of the system needs to be improved [11]–[13].

With the aim of solving the aforementioned problem, this analysis designs an Ant Colony algorithm for system scheduling based on LTPNs. The main contributions are as follows:

(1) The logistics scheduling model based on LTPN is established. Based on it, the scheduling process of ECL is analyzed with concrete examples.

(2) The concept of pheromone is introduced into the transition of the system, and the Ant Colony algorithm (ACA) is used in network processing. Heuristic factors is set on the time boundaries.

(3) Data experiments were performed on the E-Commerce Logistics model. The correctness and effectiveness of the proposed algorithm are verified by experiments.

The rest of this paper is organized as follows. Some of the basic knowledge are reviewed in Section II, for example, the Logical Petri Nets, Logical Time Petri Nets. In Section III, the model of ECL based on LTPNs is established and the scheduling scheme is analyzed. In Section IV, the Ant Colony algorithm (ACA) via LTPNs is proposed and the effectiveness of the algorithm is verified. The Algorithm complexity analysis and experimental verification is done in this part. Section V concludes this work.

II. PRELIMINARIES

This section briefly reviews the concepts of Logical Petri Nets (LPNs) and Logical Time Petri Nets (LTPNs). In order to describe the characteristics of e-commerce logistics better and implement ant colony algorithm into the scheduling process, LTPNs was selected as the description structure in this paper. The rest concepts can be found in the references [10]–[15].

A. LOGICAL PETRI NETS (LPNs)

Definition 1 (Logical Petri Nets): LPNs = (P, T, F, I, O, m) is an LPNs where:

(1) P is a finite set of places;

(2) $T = TI \cup TO$ is a finite set of transitions with $T \cup P \neq \varnothing$, $T \cap P = \varnothing$, $TI \cap TO = \varnothing$ and $\forall t \in T$: ${}^{\bullet}t \cap t^{\bullet} = \varnothing$, where: TI, TO is defined as a set of logical input transitions.

(3) $F \subseteq (P \times T) \cup (T \times P)$ is a set of arcs;

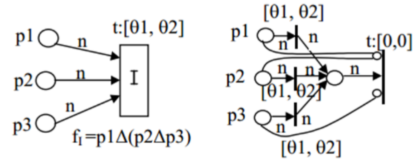
(4) I is a mapping function that map the values from a logical input transition to another one, i.e., $\forall t \in TI$: $I(t)=fI(t)$;

(5) O is a mapping function from a logical output transition to another one, i.e., $\forall t \in TO$: $O(t) = fO(t)$;

(6) m: $P \rightarrow \{0, 1\}$ is a marking function where $\forall p \in P$: $m(p)$ is the number of token sin p;

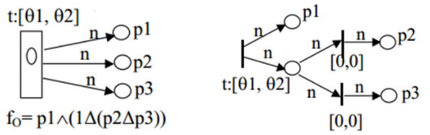
(7) Transition firing rules:

(a) $\forall t \in TI$: if $fI(t)|m = \bullet T \bullet$, i.e., ${}^{\bullet}t$ satisfy a logical input expression $fI(t)$ at m, then t is enabled at m, denoted by $m[t>$; if t is enabled, then it can fire, and generates a new



(a)component in LTPN (b)component in TPN

FIGURE 1. Logical input time transition component in LTPN and TPN.



(a)component in LTPN (b)component in TPN

FIGURE 2. Logical output time transition component in LTPN and TPN.

state m'. $\forall p \in {}^{\bullet}t$: $m'(p) = 0$, $\forall p \in t^{\bullet}$: $m'(p) = m(p)+1$, and $\forall p \notin {}^{\bullet}t \cup t^{\bullet}$:$m'(p) = m(p)$;

(b) $\forall t \in TO$: if $\forall p \in {}^{\bullet}t$: $m(p) = 1$, then t is enabled at m, and it can fire and its firing generates a new marking m'. $\forall p \in {}^{\bullet}t$: $m'(p) = m(p)$-1, $\forall p \notin t^{\bullet} \cup {}^{\bullet}t$: $m'(p) = m(p)$, and $t^{\bullet}$ must satisfy $fO(t)|M' = \bullet T \bullet$, i.e., $t^{\bullet}$ must satisfy a logical expression $fO(t)$ at m'.

B. LOGICAL TIME PETRI NETS

Definition 2 (Logical Time Petri Nets): *LTPN= (P, T, F, M0, SI, I, O)* is a logical TPN if:

(1) *(P, T, F, M 0, SI)* is a TPN;

(2) P is composed of two disjunct subsets of places, PC and PD;

(3) T includes three disjunct subsets of transitions, i.e. $T = TG \cup TI \cup TD$, $\forall t \in TI \cup TO$: ${}^{\bullet}t \cap t^{\bullet} = \varnothing$, and $\forall t \in T$, $PC \cap {}^{\bullet}t \neq \varnothing$, $PC \cap t^{\bullet} \neq \varnothing$

(4) I is a mapping from a logical input transition to a logical input expression, i.e. $\forall t \in TI$, $I(t) = fI(t)$;

Figure 1 and Figure 2 give examples of logical input and output time transition component in LTPN and TPN, the simplicity of the LTPN expression can be clearly seen in the figure.

The above figure shows that Petri nets have a strong stimulation and expression ability of logical time, which plays an important role in the abstract expression of the system and the compression of the network scale so that the analysis complexity of Petri nets model can be reduced. Δ is a substitutable operator.

III. LOGISTICS SCHEDULING SYSTEM MODEL

There are many advantages to modeling an ECL system using LTPNs. The logical expressions can reduce the difficulty of modeling, and describe the dynamic process of the system and its logical relations more easily and intuitively. In addition, the ECL system is not only a collaborative system but also a real-time system. Participants usually perform an action task is not only concerned about the execution result of this action but also involves the movement of the implementation of the time. That is, the participants in the system to perform a task as well as the premise of considering the task

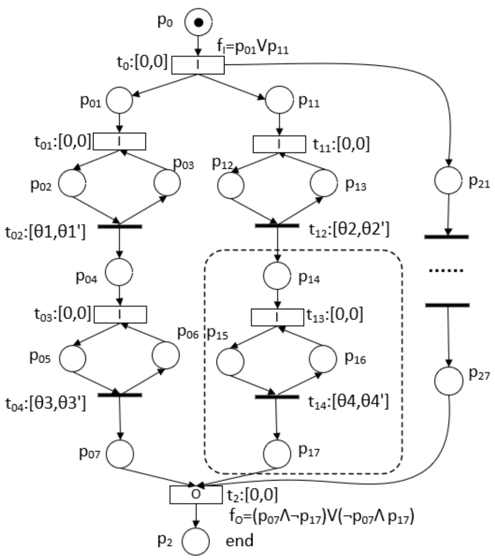


FIGURE 3. An LTPNs model for the logistics scheduling system.

and limit its execution time. For example, a consumer submitted a logistic request should be responded within a certain time limit after received this request and reply or confirmation within a certain amount of time. In addition, the whole work process in the system should be a time constraint from start to end to complete. It must be completed within an agreed time or date interval. Therefore, each workflow process should have the latest completion time or date deadline, that is, the necessity of time and Logic in the model [16]–[19].

A. AN LTPNS MODEL

The transport personnel and vehicles, handling personnel and tools, loading personnel and vehicles, distribution personnel and other factors need to be considered in the logistics scheduling process. Among them, the speed of transportation and distribution has the biggest impact on the overall efficiency of the system and is the main direction of improvement. It is an important scheduling optimization problem to work in multiple teams at the same time, and how to carry out multi-vehicle and multi-task logistics distribution path planning within a single team to achieve the optimal distribution link speed. The meanings of the symbols in the model are shown in Table 1. And Table 2. The following is a logistics scheduling model, as shown in Figure 3 [20].

Assume that L1 and L2 are two task groups on the same line of business that receive tasks from the scheduling center. Similarly, it can be extended to n task groups.

To explain the figure, the meanings of the different places are shown in Table1.

The meanings expressed by different transactions are shown in Table 2.

B. LOGISTICS SCHEDULING

Taking the freight vehicle transport in the dotted frame diagram as an example, the logistics scheduling problem is illustrated by the following assuming data.

TABLE 1. Meanings of place in the model.

Place	MEANING
p_0	the State of Task Release
p_{01}, p_{11}	The Result of Distribution
p_{02}, p_{12}	Ready to Transport
p_{03}, p_{13}	State of Transport Vehicle
p_{04}, p_{14}	Goods arrived at the Storage
p_{05}, p_{15}	Ready to Delivery
p_{06}, p_{16}	Distribution Vehicle Status
p_{07}, p_{17}	Deliver to customer
p_2	End of the task

TABLE 2. Meanings of transaction in the model.

Transaction	MEANING
t_0	Task release
t_{01}, t_{11}	Receive tasks
t_{02}, t_{12}	Task assignment
t_{03}, t_{13}	Ready to transport
t_{04}, t_{14}	The goods delivery
t_2	Distribution to complete

TABLE 3. Time of transport.

	O_{00}	O_{01}	O_{02}	O_{10}	O_{11}	O_{12}
D_0	2	1	6	3	1	3
D_1	1	2				2
D_2	3		2		2	7
D_3	4	3	1	2	2	1

TABLE 4. Path of transport.

	O_{00}	O_{01}	O_{02}	O_{10}	O_{11}	O_{12}
Path	D_1	D_0	D_3	D_3	D_0	D_3

In Table 3, O_{ij} represents the transportation process, the JTH transportation sequence of goods I. D_i represents the transport time under different personnel and vehicle conditions [21]–[23].

Since it can not only analyze the real-time question but also solve the batch processing and uncertainty value transfer, LTPNs is suitable for the description of the e-commerce logistics system. The control subnet of the above resource scheduling can be directly modeled as shown in Figure 4(next page).

Where p_{ijk} represents the transportation process of O_{ij} in Dk and the figure on the arc represents the launch time cost. The optimal scheduling path is shown in Table 4 [24].

The scheduling problem is more complex, and a large model will set more rules to constrain the launch conditions. In the previous research, heuristic algorithm and genetic algorithm were used to solve the distributed resource scheduling problem. In this paper, the ant colony algorithm is applied based on the LTPNs model. The following is the algorithm rules.

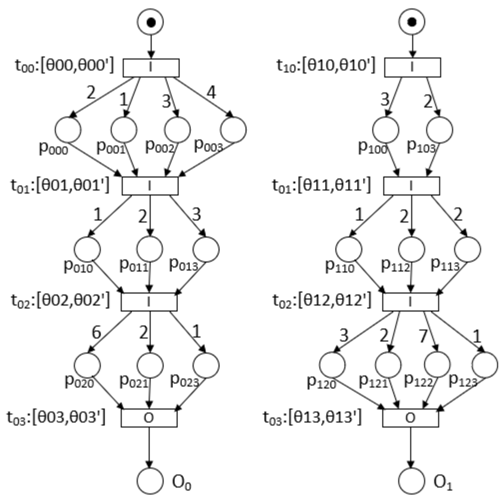


FIGURE 4. LTPNs model for the logistics scheduling.

IV. ANT COLONY OPTIMIZATION ALGORITHM RULES ON LTPNS

With optimized process control and system scheduling combined with extended Petri Net, artificial intelligence algorithms can efficiently search the state-space, thereby improving overall execution.

Ant colony algorithm is an algorithm combining positive feedback principle and heuristic algorithm. Ant algorithm is inspired by the foraging behaviors of real Ant colonies and represented by an Ant walking routes to solve the problem of a feasible solution. An Ant is to search independently the feasible solution in the solution space. Keep on walking route information of hormone, the better the quality of the solution is, the more efficient the Ant colony on the representative optimal solution route under the action of positive feedback, along with the advancement of algorithm. An ant colony optimization algorithm based on LTPNs is defined in this paper [25]–[29].

A. TERMS FOR THE ALGORITHM

By introducing the concept of pheromones to system transition, using the Ant Colony algorithm (ACA) in the processing of the network, and setting the heuristic factor in combination with the time boundary, the non-deterministic behavior can be automatically analyzed and selected in the LTPNs.

The improvement and definition of LTPNs are as follows:

Definition 3 (ALTPN): an ant colony optimization logic time Petri net is a 9 tuple.

ALTPN = (P, T, F, M0, SI, I, O;τ,η), including:

(1) (P, T, F, M0, SI, I, O) is an LTPNs;

(2) τ: $T \rightarrow R^+$ is changed by mapping function, R^+ is a positive number, for t∈T, τ(t) is the amount of pheromone placed on the transition;

(3) η: T→R+ is the heuristic factor mapping function of the transition, on t∈T, η(t) is the heuristic factor of the transition. Initially, place the same number of pheromones on each transition. ↑SI(t) represents the upper limit of transition time, which can also be taken the lower limit or the median, and a is a constant.

For any transition ti, the initial pheromone amount τ0(ti) is set to (1):

$$\tau 0(\mathrm{ti}) = \frac{a}{|T| \sum_{t \in T} \uparrow SI(t)} \tag{1}$$

Definition 4 (Enforceable Transition): a transition are enforceable if and only if:

(1) $t_f \in En(M)$; t_f is enabled;

(2) t_f is not outdated and not conflicting with transitions that have been or are being implemented.

Definition 5 (Heuristic Factor): t^* represents the most recently implemented transition, and $D(t^*, t_i)$ represents the implementation time interval of transition t_i with respect to t^*. $\uparrow D(t^*, t_i)$ represents the upper bound of $D(t^*, t_i)$.

Heuristic factors can be dynamically enlightened by the upper bound:

$$\eta(\mathrm{t_i}) = \frac{1}{\uparrow D(t^*, ti) + 1} \tag{2}$$

Definition 6 (Pheromone Update Rule): Pheromones will be updated according to the following rules:

$$\tau'(\mathrm{t_i}) = (1-\rho)^* \tau(\mathrm{t_i}) + \rho \frac{1}{Lop} \tag{3}$$

$\rho(0< \rho <1)$ is a parameter, and Lop is the length of the current optimal path time.

B. ANT COLONY ALGORITHM

According to the above introduction, we provided the following algorithm.

Algorithm 1 Ant Colony Algorithm Based on LTPNs

Input: LTPNs, max num of ant(MaxA), max loop time(NL).
Output: the optimal path

```
Initialize;
Ant num m=0; the loop time n=0;
  for (n=0; n<=NL; n++) do
    for (t=0..n) do
      ti.pheromone= τ0(ti);
    end for
    for (m=0;m<=MaxA; m++ ) do
      computate implementable transition sets;
      choose the transition by logical conditions;
        if (implementable transition)
          update ti.pheromone;
          update ti.(heuristic factor);
        else continue;
        end if
      end for
     update the one Loop optimal path pheromone;
 if n>NL
 End if
 return optimal path.
```

There are two types of solutions to the problem of system scheduling:

One solution is to adopt the heuristic search algorithm, generate a reachable graph according to the heuristic function, and then select the best path within it. However, since heuristic search only has limited information, it can be difficult to predict certain behaviors of state-space during further search. Therefore, a heuristic search may not provide the optimal solution to a problem. Furthermore, heuristic schemes must create significant accessible space to accommodate analysis, leading these schemes to consume a large amount of space resulting in low execution efficiency, primarily in large-scale, complex systems.

An additional scheduling optimization method would be to rely upon intelligent algorithms. However, such algorithms bring with them their own challenges. For example, genetic algorithms are challenging in their complexity, with the algorithm needing to carry out operations related to chromosome coding and decoding as well as mutation operation accessibility judgment.

C. ALGORITHM ANALYSIS

Time complexity and space complexity are important indexes for algorithm. The complexity of the algorithm reflects the order of magnitude that the execution time of the program increases with the increase of the input scale. Post-event statistical methods are more dependent on the computer hardware, software, and other environmental factors, sometimes easy to cover up the merits of the algorithm itself. Therefore, the method of advance analysis and estimation is often adopted. This part mainly analyzes the time and space complexity of ACA and GA algorithm.

It can be known from the above algorithm that the time complexity of the Ant Colony algorithm Based on LTPNs is:

$$O(m^*n^*L^*|T|^2) \quad (4)$$

where m is the number of ants, n is the time of iterations, |T| is the number of transitions, and L is the path length of the solution.

The spatial complexity of the algorithm is:

$$O(|T|^2 + L) \quad (5)$$

Since only the space of intermediate variables and the storage space of one path are needed, the space complexity of this algorithm is very low.

Compared with heuristic search methods and genetic algorithms, Ant Colony Algorithm Based on LTPNs has obvious advantages in time and space complexity.

Heuristic algorithm: need to save all (or part) of the state class tree, needs more spaces:

$$O(2L^*|T|2) \quad (6)$$

Genetic algorithm: if using a genetic algorithm for optimal dispatch of Petri nets, its selection operation time:

$$O(Q^*L^*|T|2) \quad (7)$$

TABLE 5. Logistic transportation process.

	Order1	Order2
1	V1/V2	V1/V3/V4
2	V2/V3/V4	V1/V2/V3
3	V1/V2/V4	V4

TABLE 6. Logistic transportation time.

		V1	V2	V3	V4
Order1	Step1	15	20	/	/
	Step2	/	20	25	30
	Step3	20	20	/	25
Order2	Step1	15	/	20	25
	Step2	25	25	30	/
	Step3	/	/	/	30

The crossover operation to:

$$O(Pc^*Q^*L) \quad (8)$$

Mutation operators need to:

$$O(Pm^*2L/2^*|T|2) \quad (9)$$

where Q is population, Pc is crossover probability, Pm is mutation probability.

So the genetic algorithm's time complexity is:

$$O[N^*(Q^*L^*|T|2 + Pm^*2L/2^*|T|2)] \quad (10)$$

By calculating the time complexity and space complexity above, the complexity of the ACA is better than GA.

D. EXPERIMENT

E-commerce logistics scheduling problem has different degrees of complexity, which is similar and different from many practical production scheduling problems. The production scheduling problem has been studied in many researches. In this experiment, experimental data are simulated according to actual cases, and the experimental process is an appropriate simplification and abstraction of the actual process. Finally, the obtained problem is a typical NP-hard problem, and its research has important theoretical significance and engineering value.

The experimental examples are as follows: ECL has two types of logistics work, each type of work has three logistics orders, each order is divided into three steps, each step has more than one vehicle to complete the task. Priority should be given to the vehicle in front. For example, in the second step of order 1, when v2, v3, and v4 are all available, v2 is preferred.

The experiment is run in MATLAB. The logistics transportation processes are shown in Table 5, and the transportation time in Table 6.

TABLE 7. Scheduling results of GA.

Scheduling results	times
135	16
140	3
155	1

This problem is a typical small-batch, multi-variety scheduling problem. The system has the characteristics of a multi-processing path, equipment priority and equipment maintenance.

Reference [15] set crossover probability Pc = 0.9 and mutation probability Pm =0. 2, initial population Q = 100, number of iterations N = 100, generation gap G =0. 85.

Set Ant Colony algorithm parameter as: number of ants m = 20, iteration times. The number n = 100, heuristic factor beta = 10, pseudo-random ratio q0 = 0.4, letter P = 0.1.

Table 7 shows the experimental results of GA.

The Ant Colony algorithm method gets the scheduling results 135 for 20 times. It means the algorithm obtains the optimal solution every time.

Because of the parameter's randomness of the GA, the Petri net scheduling method obtains the optimal solution in most cases. In contrast, ACA has better scheduling performance than GA.

V. CONCLUSION

In this paper, LTPNs is selected for system modeling, the concept of ant pheromone was added into transition, and the ant colony optimization rules are integrated into dynamic operation by combining heuristic factors and dynamic scheduling. This algorithm has a high degree of integration with the network. It introduces the concept of pheromones to system transition. Compared with heuristic scheduling, space efficiency is high because there is no need to construct and store the accessible space. Compared with other intelligent algorithms, such as genetic algorithms, ACA reduces the complexity of algorithms, thus improving development and computing efficiency. In the scheduling of complex systems, multi-objective optimization is involved, which will be a further consideration.

REFERENCES

[1] Z. Zhu, "Modeling of intelligent E-commerce logistics service system based on object-oriented time Petri nets," *CAAI Trans. Intell. Syst.*, vol. 13, pp. 303–313, Feb. 2018.
[2] Y. Y. Wang and Y. Y. Du, "Conformance checking based on extended footprint matrix," *J. Shandong Univ. Sci. Technol., Nature Sci.*, vol. 37, no. 2, pp. 9–15, 2018.
[3] L. Liu, W. Liu, and Y. Du, "Business process modeling and analysis based on queue logical Petri Nets," *Int. J. Softw. Eng. Knowl. Eng.*, vol. 29, pp. 115–137, Jan. 2019.
[4] J. Wang, Y. Du, and S. Yu, "Coloured Logic Petri Nets and analysis of their reachable trees," *Enterprise Inf. Syst.*, vol. 9, no. 8, pp. 900–919, 2014.
[5] Y. Du, L. Qi, and M. Zhou, "A vector matching method for analysing logic Petri nets," *Enterprise Inf. Syst.*, vol. 5, no. 4, pp. 449–468, 2011.
[6] X. Guo, S. Wang, D. You, Z. Li, and X. Jiang, "A siphon-based deadlock prevention strategy for S^3PR," *IEEE Access*, vol. 7, pp. 86863–86873, 2019.
[7] W. Liu, L. Wang, Y. Du, and M. Li, "Deadlock property analysis of concurrent programs based on Petri net structure," *Int. J. Parallel Program.*, vol. 45, pp. 879–898, Aug. 2017.
[8] P. Wang, W. Liu, Y. Du, M. Zhou, and C. Yan, "Extended logical Petri nets-based modeling and analysis of business processes," *IEEE Access*, vol. 5, pp. 16829–16839, 2017.
[9] W. Liu, L. Wang, X. Feng, M. Qi, C. Yan, and M. Li, "Soundness analytics of composed logical workflow nets," *Int. J. Parallel Program.*, vol. 47, pp. 709–724, Aug. 2019.
[10] W. Liu, Y. Du, and C. Yan, "Soundness preservation in composed logical time workflow nets," *Enterprise Inf. Syst.*, vol. 6, no. 1, pp. 95–113, 2012.
[11] Y. Du and Y. Ning, "Property analysis of logic Petri nets by marking reachability graphs," *Frontiers Comput. Sci.*, vol. 8, pp. 684–692, Aug. 2014.
[12] Y. Y. Du, Y. H. Ning, and L. Qi, "Reachability analysis of logic Petri nets using incidence matrix," *Enterprise Inf. Syst.*, vol. 8, no. 6, pp. 630–647, 2013.
[13] M. G. H. Omran and S. Al-Sharhan, "Improved continuous Ant Colony Optimization algorithms for real-world engineering optimization problems," *Eng. Appl. Artif. Intell.*, vol. 85, pp. 818–829, Oct. 2019.
[14] L. Pan, Z.-J. Ding, and G.-Q. Guo, "Time Petri net model with mixed semantics," *J. Softw.*, vol. 22, no. 6, pp. 1199–1209, 2011.
[15] H. A. O. Dong, C.-J. Jiang, and L. Lin, "Petri net based modeling and GA based scheduling for FMS," *Chin. J. Comput.*, vol. 28, no. 2, pp. 201–208, 2010.
[16] S. Wang, D. You, and M. Zhou, "A necessary and sufficient condition for a resource subset to generate a strict minimal siphon in S 4PR," *IEEE Trans. Autom. Control*, vol. 62, no. 8, pp. 4173–4179, Aug. 2017.
[17] H. Dou, K. Barkaoui, H. Boucheneb, X. Jiang, and S. Wang, "Maximal good step graph methods for reducing the generation of the state-space," *IEEE Access*, vol. 7, pp. 155805–155817, 2019, doi: 10.1109/ACCESS.2019.2948986.
[18] M. Zhou, "Modeling, analysis, simulation, scheduling, and control of semiconductor manufacturing systems: A Petri net approach," *IEEE Trans. Semicond. Manuf.*, vol. 11, no. 3, pp. 333–357, Aug. 1998.
[19] G. Liu and C. Jiang, "Petri net based model checking for the collaborative-ness of multiple processes systems," in *Proc. IEEE Int. Conf. Netw., Sens., Control*, Wuerzburg, Germany, Apr. 2016, pp. 1–6.
[20] Y. Du, L. Qi, and M. Zhou, "Analysis and application of logical Petri nets to E-commerce systems," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 44, no. 4, pp. 468–481, Apr. 2014.
[21] L. Qi, M. Zhou, and W. Luan, "An emergency traffic light strategy to prevent traffic congestion," in *Proc. IEEE Int. Conf. Netw, Sens., Control (ICNSC)*, Mexico City, Mexico, Apr. 2016, pp. 1–6.
[22] Y. Du and C. Jiang, "On the design and temporal Petri net verification of grid commerce architecture," *Chin. J. Electron.*, vol. 17, no. 2, pp. 247–251, 2008.
[23] Y. Y. Du, C. J. Jiang, and M. C. Zhou, "Modeling and analysis of real-time cooperative systems using Petri nets," *IEEE Trans. Syst., Man, Cybern. A, Syst. Humans*, vol. 37, no. 5, pp. 643–654, Sep. 2007.
[24] Y. Du, C. Jiang, and M. Zhou, "A Petri-net-based correctness analysis of Internet stock trading systems," *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 38, no. 1, pp. 93–99, Jan. 2008.
[25] Y. Du, C. Jiang, and M. Zhou, "A Petri net-based model for verification of obligations and accountability in cooperative systems," *IEEE Trans. Syst., Man, Cybern. A, Syst. Humans*, vol. 39, no. 2, pp. 299–308, Mar. 2009.
[26] H. Qi, Y. Du, and W. Liu, "Process model repairing method based on reachable markings," *J. Shandong Univ. Sci. Technol., Nature Sci.*, vol. 36, no. 1, pp. 118–124, Feb. 2017.
[27] A.-C. Huang, L.-C. Fu, M.-H. Lin, and S.-Y. Lin, "Modeling, scheduling, and prediction for wafer fabrication: Queueing colored Petri-net and GA based approach," in *Proc. IEEE Int. Conf. Robot. Automat.*, Washington, DC, USA, May 2002, pp. 3187–3192.
[28] X. Gang and Z. Wu, "Deadlock-free scheduling method using Petri net model analysis and GA search," in *Proc. Int. Conf. Control Appl.*, Glasgow, U.K., vol. 2, Sep. 2002, pp. 1153–1158.
[29] W. Liu and Y. Du, "Modeling multimedia synchronization using Petri nets," *Inf. Technol. J.*, vol. 8, no. 7, pp. 1054–1058, 2009.

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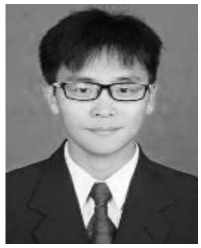

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