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PERFORMANCE ANALYSIS AND OPTIMIZATION METHOD BASED ON PETRI NET FOR MANUFACTURING EXECUTION SYSTEM

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Abstract. The Manufacturing Execution System (MES) is a critical component of intelligent manufacturing systems, enabling the automation and intelligent control of production processes. However, conventional MESs generally lack sufficient flexibility in coping with process reconfiguration and dynamic resource variations, thereby resulting in production bottlenecks and prolonged manufacturing time. To alleviate production bottlenecks while reducing overall manufacturing time, we propose a modeling, analysis, and resource allocation optimization framework for

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MESs. This framework employs rewritable timed Petri nets (RTPNs) to model and analyze MES behavior. Furthermore, a resource allocation optimization algorithm is developed to minimize production time. A clothes customization manufacturing system is adopted as a case study to demonstrate the effectiveness of the proposed method. The production process is reconstructed and optimized based on the RTPN model, and system performance is validated through simulation. Experimental results indicate that the proposed method significantly reduces production blocking and waiting rates, thereby improving overall operational efficiency.

Keywords: Manufacturing execution system, intelligent manufacturing system, resource allocation optimization, Petri net

1 INTRODUCTION

The manufacturing execution system (MES) is a workshop control system that manages the entire manufacturing system according to the production plan, material management strategy, quality standard, quality inspection, cost accounting, etc., formulated by the management department, and supervises and controls each process in real time. It is the information bridge between manufacturing and management.

Research on MES primarily focuses on system architecture design and overall process optimization. Prior studies have investigated MES architectures by integrating services from multiple independent work cells into a unified production system, with the aim of achieving trustworthy, reconfigurable, and interoperable manufacturing systems [1]. Furthermore, augmented reality technologies have been incorporated into MES to support remote assistance applications [2]. In addition, system flexibility has been investigated from the perspectives of production loss and system capacity, with particular attention to the impacts of system configuration, buffer capacity, and related factors [3]. Machine selection strategies that consider system reconfiguration capability have been proposed to reduce machine utilization and maintenance costs [4]. To address MES scheduling under uncertainty, intelligent optimization approaches, such as improved artificial immune system algorithms, have been introduced to enhance production quality [5].

Modeling and simulation of manufacturing systems can be utilized to analyze performance, verify correctness, and evaluate efficiency. Formal description tools with both mathematical and graphical expressions, such as Petri net (PN), can depict the relationships between different parts of the manufacturing system, as well as reflect event sequencing, parallelism, synchrony, and asynchrony [6, 7]. However, MES production structures are dynamic, and PN is incapable of illustrating system reconfiguration processes. As a solution, rewritable PN (RPN) was introduced to model and analyze system reconfiguration processes [8]. Despite this, achieving optimization of the system production processes utilizing RPN remains unresolved.

We propose a modeling and optimization method for MES, that can analyze and optimize the production bottleneck to improve the production efficiency of the MES. In this paper, our main contributions are as follows:

1. The modeling analysis and resource optimization method of MES based on rewritable timed PN (RTPN) is proposed.
2. We take the clothes customization manufacturing system as a case study. Modeling analysis and optimization of the system is based on RTPN.
3. The clothes customization manufacturing system before and after rewriting based on the proposed method is analyzed through experiments.

The remainder of this paper is organized as follows. Section 2 reviews the related work. Section 3 presents the proposed modeling analysis and resource optimization methods for MES. Section 4 demonstrates the effectiveness of the proposed approach through a garment customization MES. Section 5 provides the experimental results and analysis. Section 6 concludes the paper and discusses future research directions.

2 RELATED WORK

Recent studies have proposed various approaches to address resource allocation and optimization problems in MES. Reinforcement learning-based methods have been used to cope with unstable wireless communication channels and limited connection reliability among smart mobile resources, improving collaborative manufacturing performance in smart factories [9]. In addition, resource allocation has been investigated from a system-level perspective through multi-layer modeling and optimization frameworks. By formulating the IT resource placement problem as a mixed-integer linear programming (MILP) model and leveraging open-source optimization tools, such approaches enable coordinated deployment of applications and computing resources across heterogeneous layers, ranging from on-device platforms to cloud infrastructures, thus improving system efficiency and adaptability [10]. Furthermore, evolutionary optimization techniques have been introduced to optimize execution delay and energy consumption in MES. Multi-objective genetic algorithms have been applied to multi-workflow scheduling problems while explicitly considering resource starvation, where dynamic adjustment of task execution locations contributes to improved system performance and resource utilization [11]. Despite their effectiveness in specific optimization scenarios, the above approaches generally lack explicit modeling and reconfiguration mechanisms to accommodate dynamic system changes. In addition, they provide limited support for formal analysis, system visualization, and structural interpretability. In contrast, PNs offer rigorous mathematical foundations and well-established analytical theories, enabling systematic modeling, analysis, and optimization of MES with strong formal guaranties.

PNs have been widely applied to model and analyze manufacturing systems, owing to their strong descriptive capability and rigorous analytical foundations. Existing studies have adopted PNs as the underlying modeling framework for MES analysis and scheduling. In particular, PN-based models have been integrated with the model predictive control to support feedback-driven scheduling mechanisms in MES [12]. Furthermore, PNs have been extensively employed to address scheduling problems in manufacturing systems that are prone to deadlock. By exploiting the structural properties of PNs, deadlock-free scheduling strategies have been developed with the objective of minimizing production completion time [13, 14]. Moreover, to capture the temporal characteristics of real-world manufacturing processes, timed Petri nets (TPNs) were introduced by Zuberek through the incorporation of timing information into classical PN models, making them suitable for the performance evaluation of discrete-event systems [15].

Building upon TPNs, timed weighted marked graphs, as a subclass of TPNs, have been proposed to investigate optimal resource allocation strategies in manufacturing systems [16]. In addition, heuristic search-based scheduling approaches grounded in TPN models have been developed to transform given job sequences into feasible schedules that satisfy both deadlock-free and no-wait constraints, while minimizing the makespan [17, 18]. These methods provide effective solutions for manufacturing systems subject to deadlock and waiting constraints, thereby improving overall production efficiency.

In addition, other extended PNs, such as Colored PNs and Labelled PNs, can also be used for analyzing and optimizing manufacturing systems. In [19], Nabi and Aized propose a method for modeling, simulating, and analyzing the manufacturing system of multi-variety production. This method uses colored PN to model the manufacturing system and analyze the throughput and average production cycle of the system to evaluate the system's performance. Labelled timed Petri nets (LTPNs) have been proposed to transform the pattern diagnosability problem of discrete-event systems into the verification of linear temporal properties, thereby enabling fault diagnosis within such systems [20]. Overall, existing studies employ PNs, TPNs, and other extended PN models to analyze and optimize manufacturing systems with fixed production processes.

However, above PNs with immutable structures are unable to effectively analyze systems with dynamic changes. Consequently, it is difficult to formally describe and analyze the properties of dynamic manufacturing systems. In contrast, rewritable Petri nets (RPNs) introduce rewriting mechanisms that permit structural modifications, enabling flexible modeling of practical systems with mutable states and significantly extending the expressive power and application scope of PNs.

RPNs represent an extended class of PN that enable the modeling and simulation of concurrent systems with dynamic structural changes [8]. To exploit this capability for adaptive manufacturing environments, net rewrite systems have been proposed as a subclass of RPNs to support system reconfiguration, thereby enabling structural adaptation of monitoring and control systems [21]. However, such approaches generally lack formal verification of critical system properties, including boundedness and liveness. To address the lack of formal property verification in existing net rewrite systems, improved net rewrite systems (INRSs) have been introduced to model reconfigurable manufacturing systems by decomposing them into modular components, while guaranteeing the preservation of the original system properties [22]. However, even with such property preservation, system reconfiguration may still lead to deadlock situations. To mitigate this limitation, RPN-based deadlock prevention strategies have been developed to reconstruct deadlock-prone systems and formally verify the correctness of dynamically reconfigured systems, including properties such as availability, fault estimation, and deadlock detection, thereby ensuring system viability prior to deployment [23, 24]. Despite these advances, existing RPN-based approaches primarily focus on system modeling, verification, and correctness assurance, while providing limited support for production process optimization and efficiency improvement.

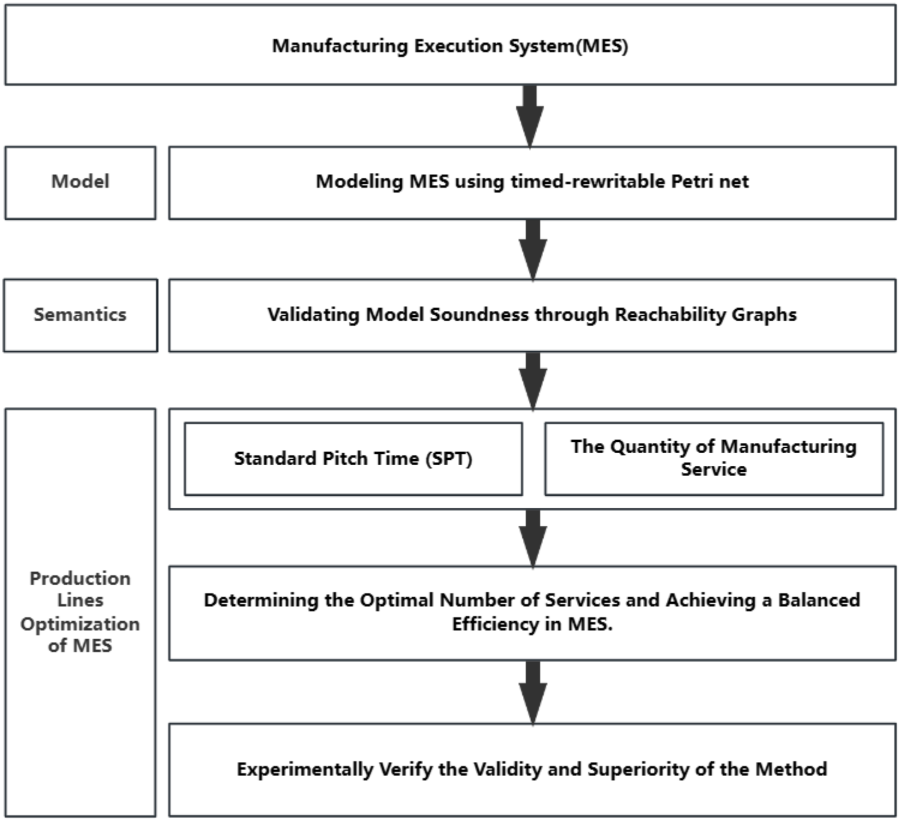


Figure 1. Overall framework

3 MODELING ANALYSIS AND RESOURCE OPTIMIZATION METHOD

This paper proposes a timed rewritable Petri net for modeling and analyzing MES to ensure the reliability of production processes. Based on the analytical results, a production line balancing optimization algorithm is developed to improve production efficiency in MES. For clarity, we first introduce Petri nets, timed Petri nets, and rewritable timed Petri nets, followed by a detailed description of the proposed optimization algorithm. The overall framework of this study is illustrated in Figure 1.

3.1 Modeling Analysis of MES

Definition 1 (Petri net [25])**.** A Petri net is a 4-tuple

$$PN = (P, T, F, M_0),$$

where

- P is a finite set of places;
- T is a finite set of transitions such that $P \cap T = \varnothing$;
- $F \subseteq (P \times T) \cup (T \times P)$ is a set of directed arcs;
- M_0 is the initial marking of PN.

A marking of PN is a mapping

$$M : P \rightarrow \mathbb{N} = \{0, 1, 2, \ldots\},$$

which assigns a non-negative integer number of tokens to each place. For a place $p \in P$, $M(p)$ denotes the number of tokens in place p under marking M.

Definition 2 (timed Petri net [26])**.** A timed Petri net (TPN) is a 5-tuple $\Sigma_0 = (P, T, F, M_0, DI)$, where

- (P, T, F, M_0) is a basic PN;
- DI: $T \rightarrow A_0$ is a timing function that assigns a time value in A_0 to each transition. $\forall t \in T$, $DI(t) = a$ means transition t will spend time a to complete fire.

Definition 3 (Rewritable timed Petri net)**.** A rewritable timed Petri net (RTPN) is a 2-tuple $\Sigma = (\Re, \Sigma_0)$, where

- $\Re = \{r_1, r_2, \ldots, r_n\}$ is the finite rewritable rules set;
- Σ_0 is the initial TPN;
- $r \in \Re$ is a 5-tuple $r = (L, R, {}^\bullet\tau, \tau, \tau^\bullet)$, where

1. $L = (P_L, T_L, F_L, DI_L)$ and $R = (P_R, T_R, F_R, DI_R)$ denote the left-hand side and the right-hand side of a rewriting rule r, respectively. Here, P_L, T_L, and F_L represent the sets of places, transitions, and arcs of the left-hand side L, respectively, and DI_L denotes the timing function associated with L. Similarly, P_R, T_R, F_R, and DI_R represent the corresponding components of the right-hand side R.
2. $\tau \subseteq (P_L \times P_R) \cup (T_L \times T_R) \cup (DI_L \times DI_R)$ is the binary relation of the rewriting rule r. Specifically, the places, transitions and timing functions on the left-hand side are related to the corresponding places, transitions and timing functions on the right-hand side. That is,

$$\forall p_1 \in P_L \wedge \exists p_2 \in P_R : \langle p_1, p_2 \rangle \in \tau \Rightarrow p_2 \text{ is rewritten from } p_1;$$

$$\forall t_1 \in T_L \wedge \exists t_2 \in T_R : \langle t_1, t_2 \rangle \in \tau \Rightarrow t_2 \text{ is rewritten from } t_1;$$

$$\forall t_1 \in T_L \wedge \exists t_2 \in T_R : \langle DI_L(t_1), DI_R(t_2) \rangle \in \tau \Rightarrow DI_R(t_2) \text{ is rewritten from } DI_L(t_1).$$

3. ${}^{\bullet}\tau \subseteq \tau$ and $\tau^{\bullet} \subseteq \tau$ are the input interface relation and the output interface relation.
4. If a transition t fires and generates a new marking M', the process is expressed as: $(\Sigma_0, M) \xrightarrow{t} (\Sigma', M') \Leftrightarrow (\Sigma = \Sigma_0) \wedge M[t\rangle$.
5. The rewritten RTPN $\Sigma'' = (P, T, F, M, DI)$ satisfies $P = P_0 - f(P_L) + P_R$ and $T = T_0 - f(T_L) + T_R$, where the operators $+$ and $-$ denote the addition and removal of places or transitions, respectively. Here, f denotes a full embedding function that maps places (transitions) in the left-hand side to their corresponding places (transitions) in the right-hand side, i.e., $f(P_L) \subseteq P_R$ and $f(T_L) \subseteq T_R$; the detailed definition of f is provided in [8]. The arc relation F is defined as follows:

$$F'(x, y) = \begin{cases} F(x, y), & x \notin R \wedge y \notin R; \\ F_R(x, y), & x \in R \wedge y \in R; \\ \cup_{y_i \in {}^{\bullet}\tau y} F(x, y_i), & x \notin R \wedge y \in R; \\ \cup_{x_i \in \tau^{\bullet} x} F(x_i, y), & x \in R \wedge y \notin R; \end{cases} \tag{1}$$

Place $p \in P$, marking $M'(p)$ is as follow:

$$M'(p) = \begin{cases} M(p), & p \notin R; \\ M(f(p)), & p \in R. \end{cases} \tag{2}$$

Definition 4 (Soundness [26])**.** An RTPN $\Sigma = (\Re, \Sigma_0)$ is said to be *sound* if it satisfies all of the following conditions:

- The terminal marking M_{end} is the only reachable marking that contains a token in the terminal output place p_o, and no other place contains a token, i.e., $M_{\text{end}}(p_o) = 1$ and $\forall p \in P \setminus \{p_o\}$, $M_{\text{end}}(p) = 0$.
- For every marking M that is reachable from the initial marking M_0 in Σ_0, there exist transition sequences σ_1 and σ_2 such that $M_0[\sigma_1\rangle M$ and $M[\sigma_2\rangle M_{\text{end}}$. Formally, $\forall M \left(M_0[\sigma_1\rangle M \Rightarrow \exists \sigma_2 : M[\sigma_2\rangle M_{\text{end}}\right)$.
- No transition is dead in Σ. That is, for any transition $t \in T$, there exist a transition sequence σ and markings M and M' such that $M_0[\sigma\rangle M[t\rangle M'$.

The reachability graph is a fundamental tool for analyzing the properties of PNs. Each node in the reachability graph represents a marking of the system, and the firing of a transition sequence leads to a change in the marking. Based on the reachability graph, the soundness of the system can be verified [26].

3.2 Production Lines Optimization of MES

Definition 5 (Standard Pitch Time)**.** The Standard Pitch Time (SPT) is a quantitative metric for evaluating production line balance in MES, defined by the following expression:

$$SPT = \frac{H}{Q}. \tag{3}$$

H denotes the working hours per day, and Q denotes the daily output.

To ensure production line balance in an MES, each service is required to operate within specified time constraints defined by the upper pitch time (UPT) and the lower pitch time (LPT). The UPT and LPT are defined as follows:

$$\begin{aligned} UPT &= \frac{SPT}{0.95}, \\ LPT &= 2SPT - UPT. \end{aligned} \tag{4}$$

Definition 6 (Quantity of manufacturing services)**.** The quantity of each manufacturing service can be determined according to Formula (5). Specifically, A_i denotes the required number of manufacturing services of the same type as transition t_i, which is calculated as

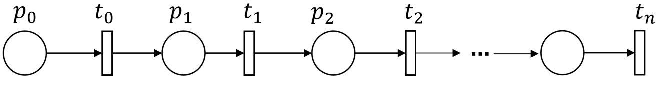
$$A_i = \text{round}\left(\frac{DI(t_i)}{SPT}\right), \tag{5}$$

where round$(\cdot)$ denotes rounding to the nearest integer.

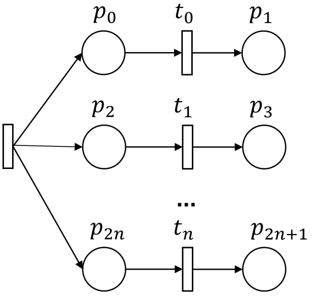
When the processing time of a service falls below the LPT, it becomes necessary to merge adjacent services to maintain production line balance. Table 1 summarizes the processing time computation for different production structures, including sequential, parallel, and loop structures, where the parameter ω denotes the number of cycles in a loop structure. The three types of production structures are illustrated in Figure 2. Based on the processing times obtained for each structure, the original hybrid manufacturing system can be transformed into an equivalent sequential service sequence. On this basis, an optimization algorithm is developed to determine the optimal number of services and to evaluate the balance efficiency of the MES. The detailed procedure for computing the optimal service quantities and balance efficiency is presented in Algorithm 1.

Index	Sequential Structure	Parallel Structure	Loop Structure
Time	$\sum_{i=0}^{n} DI(t_i)$	$\max(DI(t_i), \ldots, DI(t_n))$	$\omega \times \sum_{i=0}^{n} DI(t_i)$

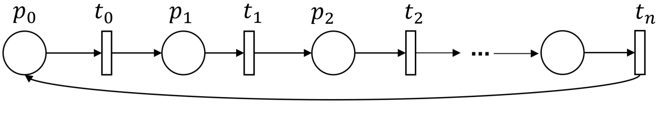
Table 1. The processing time of each production structure



a) Sequential structure



b) Parallel structure



c) Loop structure

Figure 2. Three production structures

This paper considers two cases of system reconstruction:

1. When the service time is less than the LPT, sequential services can be combined to satisfy the production balance;
2. When the service time exceeds the UPT, the same type of services need to be added in the production line.

Algorithm 1: The optimal number of each service and the balance efficiency of the MES

Input: $DI(t_i)$, SPT, LPT, UPT, n: the number of services in the MES
Output: A_i, balance efficiency Bal

```
Step 1: Compute A_i;
i = 0;
while i < n do
    k = i;
    while DI(t_k) < LPT ∧ k + 1 < n do
        DI(t_k) = DI(t_k) + DI(t_{k+1});
        k = k + 1;
    end
    if DI(t_k) > UPT then
        A_i = round(DI(t_i) / SPT);
    else
        A_i = 1;
    end
    i = k + 1;
end
Step 2: Compute balance efficiency;
j = 0;
for (i = 0; i < n; i++) do
    if A_i is defined then
        if LPT < DI(t_i)/A_i ∧ DI(t_i)/A_i < UPT then
            j = j + 1;
        end
    end
end
Bal = j / n;
```

4 ANALYSIS AND OPTIMIZATION OF THE CLOTHES CUSTOMIZATION SYSTEM

This paper takes a simple shirt customization system as a case study. In a traditional large-scale clothing manufacturing system, garment sizes and styles are fixed. In contrast, clothes customization systems must accommodate variability in the size and style of individual garments. This study focuses on size customization and reconstructs the conventional large-scale simple shirt manufacturing system to better support such variability.

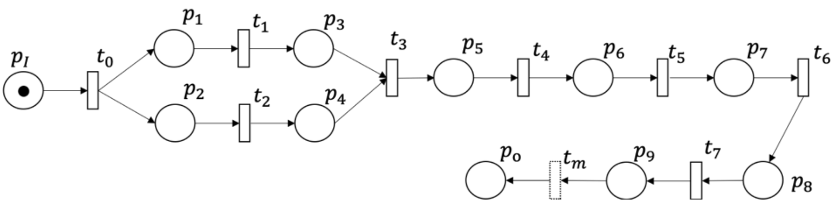


Figure 3. The TPN model of simple shirt customization system

P	Meaning	T	Meaning	$DI(t)$
p_I	user	t_0	collect data service	0 s
p_1	start of smart body-measure service	t_1	smart body-measure service	5 s
p_2	start of personalized demand collection	t_2	personalized demand collection service	5 s
p_3	completion of smart body-measure service	t_3	order management service	0 s
p_4	completion of personalized demand collection service	t_4	clothes design service	300 s
p_5	completion of the order management service and start the clothes design service	t_5	loose service	30 s
p_6	completion of clothes design service and start the loose service	t_6	CAD drawing service	300 s
p_7	completion of loose service and start the CAD drawing service	t_7	clothing layout service	180 s
p_8	completion of CAD drawing service and start the clothing layout service	t_m	nested manufacturing service	
p_9	completion of clothing layout service and start the manufacturing service			
p_o	completion of manufacturing service			

Table 2. The meaning of each places and transitions in Figure 3

The TPN model of a simple shirt customization system is illustrated in Figure 3, where transitions represent different manufacturing services, and places denote the start and completion of each service. The definitions of all places and transitions in Figure 3 are summarized in Table 2.

Among these services in Figure 3, t_m corresponds to a nested manufacturing service, as depicted in Figure 4. This nested service consists of multiple operations, including cutting, hanging, joining shoulder seams, sewing the collar, topstitching, binding labels, joining sleeve seams, cuff gripping, bottom hemming, quality control, and ironing. The definitions of the places and transitions in Figure 4 are provided in

Table 3. The number of identical services and the processing time associated with each service are provided in Table 4.

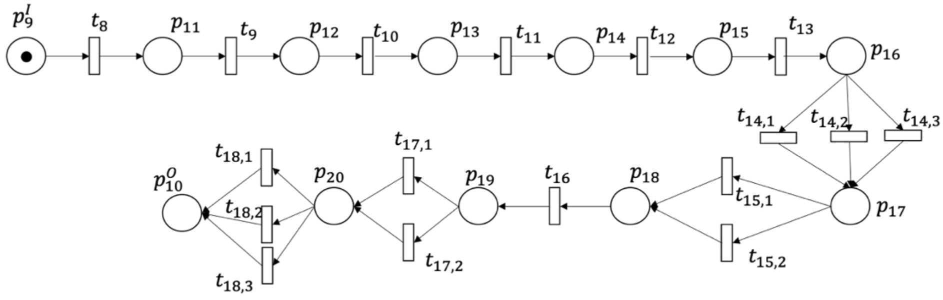


Figure 4. The TPN-based model of the nested manufacturing service t_m for simple shirt customization system

4.1 Analysis of the Simple Shirt Customization System

The factory operates for 10 hours per day and produces 700 shirts daily. Accordingly, the SPT for the simple shirt manufacturing system is calculated as 51 s, and the allowable time range for each service is constrained to [48 s, 54 s]. In the simple shirt customization system, however, the processing times of individual services do not all fall within the specified time constraints, which may result in production bottlenecks or idle states during operation. Therefore, system reconstruction is required to improve production balance. According to Algorithm 1, the smart body measurement service, personalized demand collection service, and clothes design service should be merged into a single composite service. Similarly, the loose service and the CAD drawing service need to be combined.

In a conventional large-scale simple shirt manufacturing system, 1 000 pieces of clothing can be cut at a time, and the average cutting time of each clothing is 4.5 s. In the customization system, each shirt needs to be cut separately because of different sizes, and the cutting time of each shirt is 300 s. According to Formula (5), the number of cutting services for a simple shirt customization system is 6. Therefore, the cutting service in the conventional manufacturing system needs to be reconstructed to meet the time constraints. In this paper, we reconstruct the simple shirt customization system by RTPN.

4.2 RTPN Model of Simple Shirt Customization System

According to the analysis of the simple shirt customization system, transition t_0, t_1, t_2, t_3 and t_4 can be combined into one service named t_{01234}. The time of combined service t_{01234} is 305 s. Transition t_5 and t_6 can be combined into one service named

P	Meaning	T	Meaning	$DI(t)$
p_9^I	interface of manufacturing service	t_8	cutting service	4.5 s
p_{11}	completion of the cutting service and start of the hanging service	t_9	hanging service	58 s
p_{12}	completion of the hanging service and start of the joining shoulder seam service	t_{10}	joining shoulder seam service	51 s
p_{13}	completion of the joining shoulder seam service and start of the sewing collar service	t_{11}	sewing collar service	52 s
p_{14}	completion of the sewing collar service and start of the top stitching service	t_{12}	top stitching service	50 s
p_{15}	completion of the top stitching service and start of the bound size tag service	t_{13}	bound size tag service	52 s
p_{16}	completion of the bound size tag service and start of the joining sleeve seam service	$t_{14,1}$ $t_{14,2}$ $t_{14,3}$	joining sleeve seam service	150 s (50 s)
p_{17}	completion of the joining sleeve seam service and start of the cuff gripping service	$t_{15,1}$ $t_{15,2}$	cuff gripping service	106 s (53 s)
p_{18}	completion of the cuff gripping service and start of the bottom hemming service	t_{16}	bottom hemming service	50 s
p_{19}	completion of the bottom hemming service and start of the quality control	$t_{17,1}$ $t_{17,2}$	quality control service	108 s (54 s)
p_{20}	completion of the quality control service and start of the ironing service	$t_{18,1}$ $t_{18,2}$ $t_{18,3}$	ironing service	162 s (54 s)
p_{10}^O	interface of logistics service			

Table 3. Meanings of places, transitions, and processing times of transitions in Figure 4

t_{56}, the time of combined service t_{56} is 330 s. The rewrite process of simple shirt customization manufacturing system is shown in Figure 5. According to Algorithm 1, t_{01234} needs 6 services, t_{56} needs 6 services. Similarly, the clothing layout service t_7 is decomposed into four services, as shown in Figure 6.

Figure 5 includes two rewritable rules, denoted as $r_1 = \{L_1, R_1, {}^\bullet\tau_1, \tau_1, \tau_1^\bullet\}$ and $r_2 = \{L_2, R_2, {}^\bullet\tau_2, \tau_2, \tau_2^\bullet\}$. For rule r_1, the input relation is given by ${}^\bullet\tau_1 = \{(\{t_0\}, \{t_{01234}\}), (\{DI(t_0)\}, \{DI(t_{01234})\})\}$, and the corresponding output relation is $\tau_1^\bullet = \{(\{t_4\}, \{t_{01234}\}), (\{DI(t_4)\}, \{DI(t_{01234})\})\}$. Similarly, for rule r_2, the input relation is ${}^\bullet\tau_2 = \{(\{t_5\}, \{t_{56}\}), (\{DI(t_5)\}, \{DI(t_{56})\})\}$ and the output relation is $\tau_2^\bullet = \{(\{t_6\}, \{t_{56}\}), (\{DI(t_6)\}, \{DI(t_{56})\})\}$.

However, the processing times of services t_{01234}, t_{56}, and t_7 fall outside the allowable interval [48 s, 54 s]. To address this issue, two rewrite rules r_3 and r_4 are applied to reconstruct the simple shirt customization system, as illustrated in Figure 6. The

Service	Numbers	Processing Time
cutting	1	4.5 s
hanging	1	58 s
joining shoulder seam	1	51 s
sewing collar	1	52 s
topstitching	1	50 s
bounding label	1	52 s
joining sleeve seam	3	150 s
cuff gripping	2	106 s
bottom hemming	1	50 s
quality control	2	108 s
ironing	3	162 s

Table 4. The number and processing time of each service in the simple shirt manufacturing system

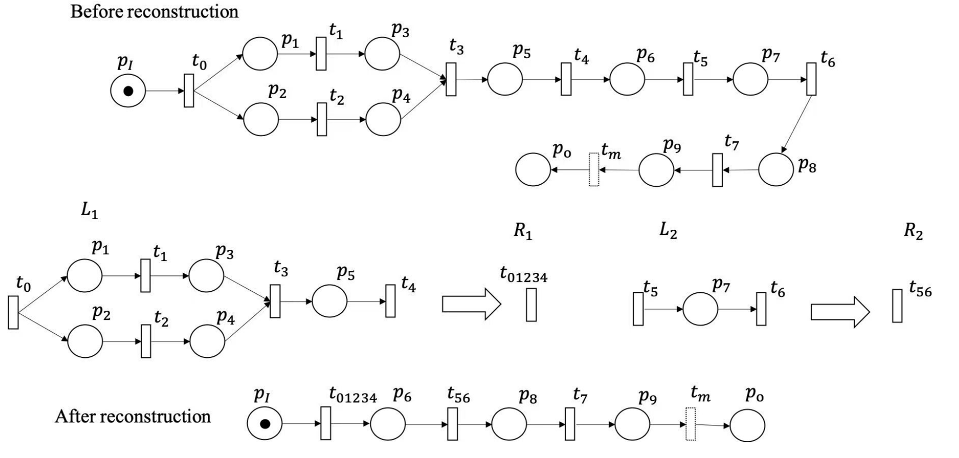


Figure 5. RTPN-based reconstruction of the simple shirt customization system using rewrite rules r_1 and r_2

first input relation is defined as

$$^{\bullet}\tau_3 = \{(\{t_{01234}\}, \{t_{01234,1}, t_{01234,2}, t_{01234,3}, t_{01234,4}, t_{01234,5}, t_{01234,6}\}), (\{DI(t_{01234})\}, \{DI(t_{01234,1}), DI(t_{01234,2}), DI(t_{01234,3}), DI(t_{01234,4}), DI(t_{01234,5}), DI(t_{01234,6})\})\},$$

and the corresponding output relation is

$$\tau_3^{\bullet} = \{(\{t_{56}\}, \{t_{56,1}, t_{56,2}, t_{56,3}, t_{56,4}, t_{56,5}, t_{56,6}\}), (\{DI(t_{56})\}, \{DI(t_{56,1}), DI(t_{56,2}), DI(t_{56,3}), DI(t_{56,4}), DI(t_{56,5}), DI(t_{56,6})\})\}.$$

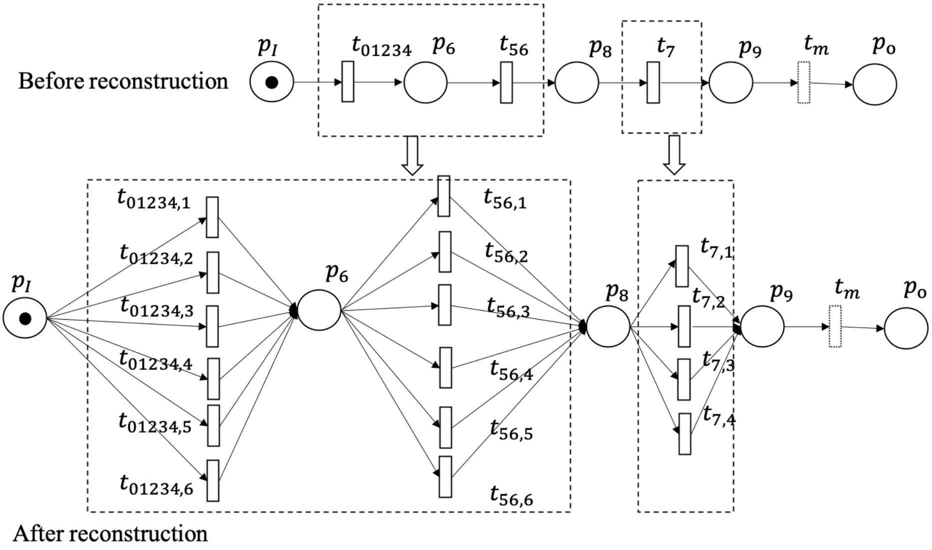


Figure 6. RTPN-based reconstruction of the simple shirt customization system using rewrite rules r_3 and r_4

The second rewrite rule is given by

$$\begin{aligned}{}^{\bullet}\tau_4 &= \tau_4^{\bullet} \\ &= \{(\{t_7\}, \{t_{7,1}, t_{7,2}, t_{7,3}, t_{7,4}\}), (\{DI(t_7)\}, \{DI(t_{7,1}), DI(t_{7,2}), DI(t_{7,3}), DI(t_{7,4})\})\}.\end{aligned}$$

Accordingly, the reconstructed model shown in Figure 6 satisfies all three soundness conditions.

In the original large-scale simple shirt manufacturing system, the processing time of the cutting service t_8 is 4.5 s. However, in the simple shirt customization system, the processing time of t_8 increases to 300 s due to the introduction of customized production requirements. As a result, the processing time of t_8 falls outside the allowable range of [48 s, 54 s], and the service needs to be reconstructed. After rewriting, the SPT of each cutting service t_8 is adjusted to 50 s. The rewriting process is illustrated in Figure 7. To verify the soundness of the reconstructed model, the reachability graph is constructed following the method described in [23]. Accordingly, the model shown in Figure 7 satisfies all three soundness conditions.

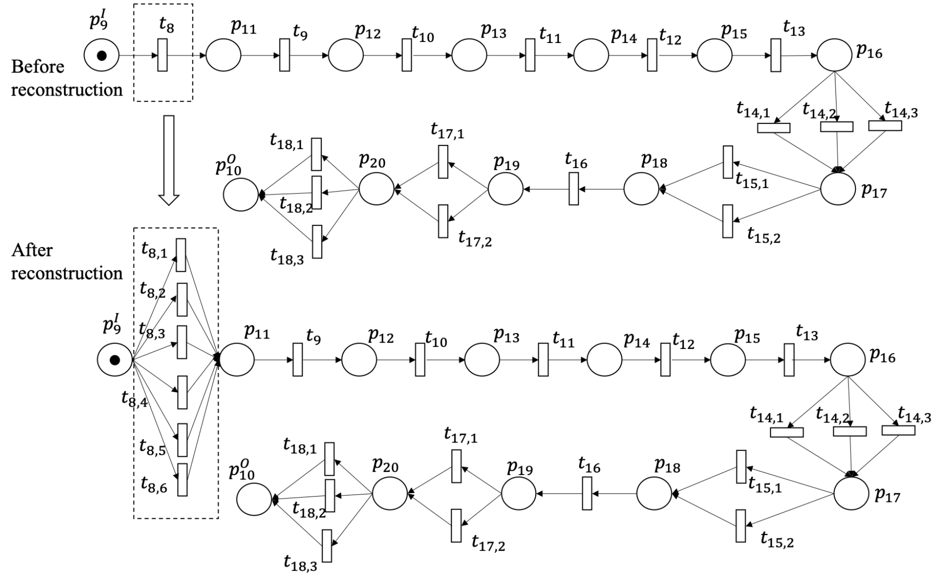


Figure 7. The rewrite process of the nested manufacturing system model of a simple shirt based on RTPN

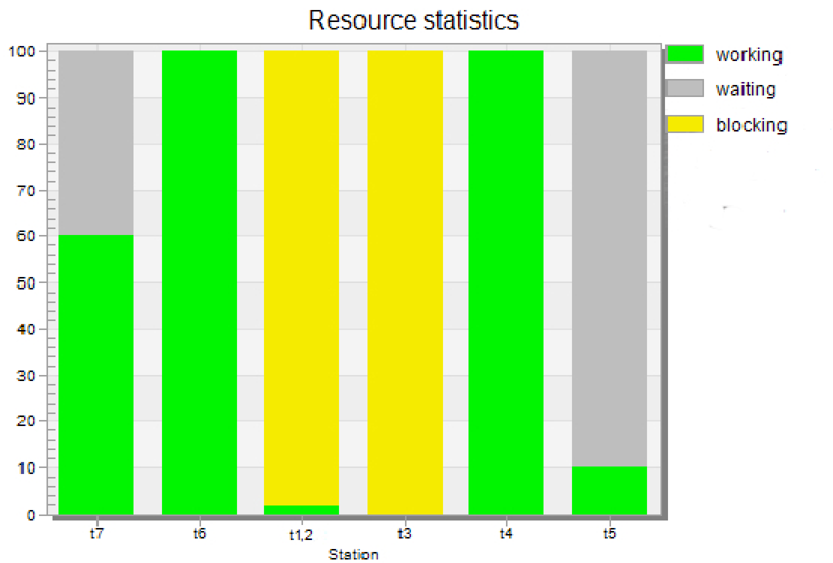
5 EXPERIMENTAL ANALYSIS

5.1 Experimental Setting

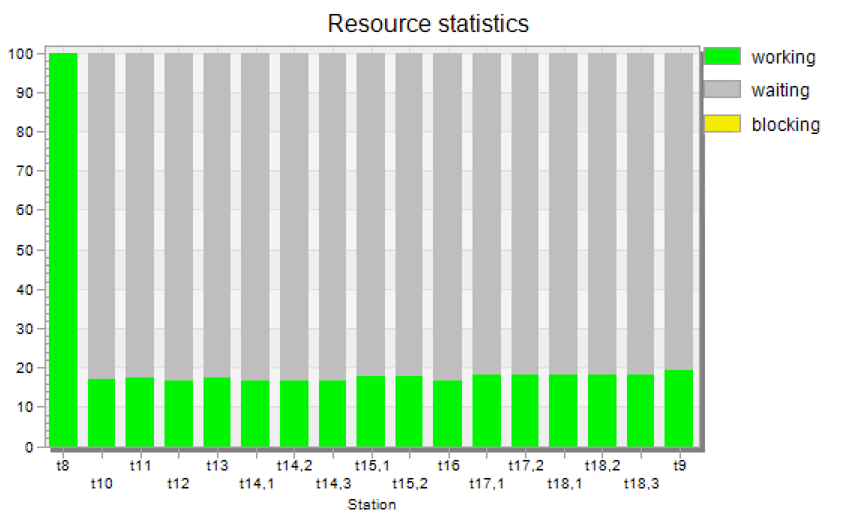
Plant Simulation is a powerful object-oriented modeling tool for simulating and analyzing complex discrete-event dynamic systems. In this study, Plant Simulation is employed to investigate the production process of a simple shirt customization system. Given the hierarchical structure of the proposed RTPN model, a corresponding hierarchical simulation framework is constructed in Plant Simulation, where the places and transitions of the RTPN are mapped to their respective entity units in the simulation environment, each initialized with a predefined processing time. Since this work primarily focuses on evaluating production efficiency, the effects of equipment failures are not considered.

5.2 Experimental Results Analysis

Based on the simulation model, Figure 8 illustrates the working states of all services before rewriting. The smart body-measure service t_1 and the personalized demand collection service t_2 operate in parallel and are therefore aggregated into a single composite service, denoted as $t_{1,2}$. The blocking rate of $t_{1,2}$ exceeds 90 %, which is mainly caused by the long processing time of the clothes design service t_4, requiring 300 s to complete, whereas $t_{1,2}$ only requires 5 s.

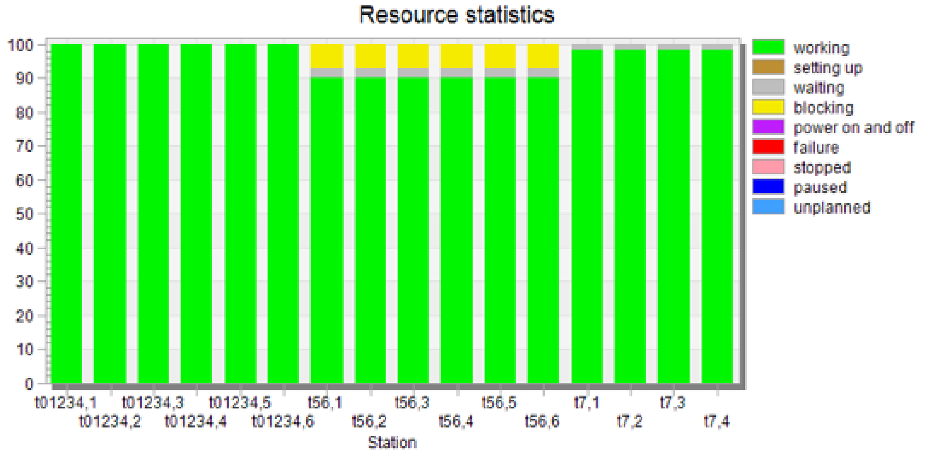


a) The working status of simple shirt customization system

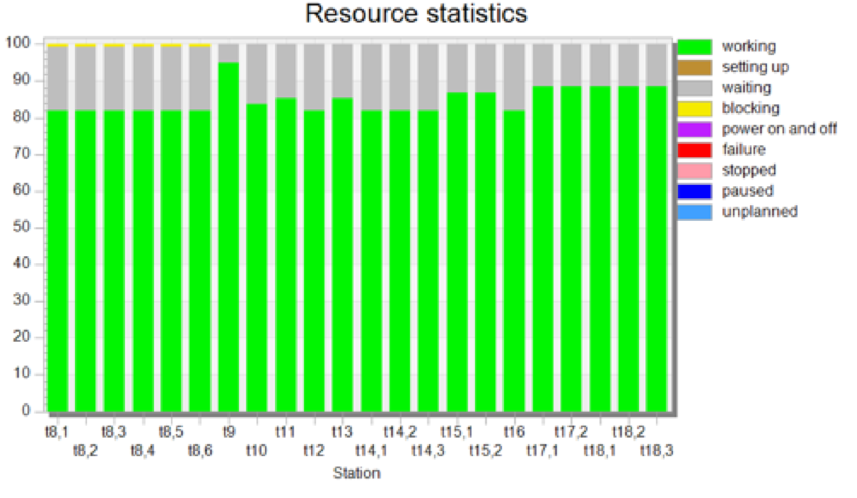


b) The working status of nested manufacturing system

Figure 8. The working status of simple shirt customization system before rewriting



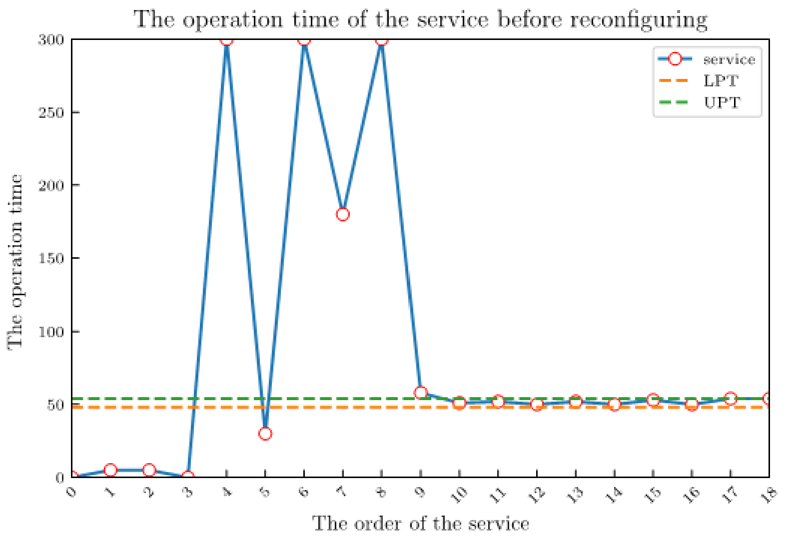
a) The working status of simple shirt customization system



b) The working status of nested manufacturing system

Figure 9. The working status of simple shirt customization system after rewriting

In the nested manufacturing service, the cutting service t_8 exhibits a 100 % working rate, while the remaining services operate at approximately 15 % utilization, with waiting rates exceeding 80 %. This imbalance arises because each cutting service t_8 requires only 4.5 s before rewriting, whereas the cutting service in the simple shirt customization system requires 300 s. Consequently, the excessive cutting service time beyond the UPT forces the other manufacturing services to remain idle while waiting for the cutting operation to complete.



a) The SPT of each service before rewriting

b) The SPT of each service after rewriting

Figure 10. The SPT of each service before and after rewriting in simple shirt customization system

The operational performance of each service in the reconstructed simple shirt customization system is illustrated in Figure 9. It can be observed that the working rate of all services exceeds 80 %, representing an improvement of approximately 65 % compared with the working rate of the original system shown in Figure 8. In addition, both the waiting rate and the blocking rate of the services are significantly reduced relative to those observed in Figure 8. These performance improvements lead to an enhanced production capacity of the system.

The SPT of each service in the simple shirt customization system before and after rewriting is shown in Figure 10. Figure 10 a) presents the SPT of each service before rewriting, where the first nine services fall outside the prescribed range of $[LPT, UPT]$ and exhibit substantial variations in SPT. In contrast, Figure 10 b) shows that only three services exceed the range of $[LPT, UPT]$, and the SPT variations among services are significantly reduced. As a result, the blocking rate and waiting rate of the reconstructed production line are decreased, leading to improved production efficiency.

6 CONCLUSION AND FUTURE WORK

This paper proposes a modeling, analysis, and optimization method for MES based on RTPN. A simple shirt customization system is employed as a case study to validate the effectiveness of the proposed approach. Experimental results demonstrate that, after system reconstruction, the working rate of each manufacturing service exceeds 80 %, indicating a significant improvement in overall production efficiency.

In this study, customization is limited to garment size, while variations in clothing styles are not considered. Future work will extend the proposed RTPN-based framework to support multi-objective customization scenarios, in which size customization, style diversity, and other production objectives are jointly optimized.

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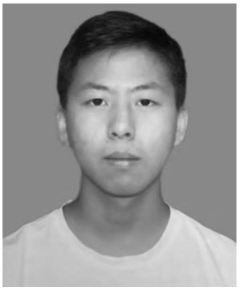

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